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METHODOLOGY FOR CONTROL OF LIFE CYCLE COSTS FOR AVIONICS SYSTEM--ETC(U)

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PREFACE

This Lecture Series No.100 on the subject of Methodology for Control of Life Cycle Costs for Avionics Systems is sponsored by the Avionics Panel of AGARD and implemented by the Consultant and Exchange Programme.

The continually increasing costs of avionics systems during acquisition and their lifetime operation is a matter of grave concern to the NATO family of nations. The NATO Governments need greater visibility and control over the life cycle costs of any weapon or avionic system.

Fortunately there have been formulated disciplined methods of providing such visibility and control over life cycle costs; that is over the development acquisition, training, operating and support and finally disposal costs.

For these reasons it has been proposed by the Avionics Panel to sponsor a Lecture Series which presents the basic principles of Avionics Systems Cost Analysis in a rapidly changing technology environment and gives proven methods of achieving significant costs savings.

The Lecture Series covers in particular the following subjects: life cycle costing, design to cost, technology environment, costing of software, modelling and applications. The new trends and advantages of control of life cycle costs for avionics systems is an important part of the Round Table Discussions organised in the two locations where the Series is presented.

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CONTENTS

and

Introduction to "Methodology for Control of Life Cycle Costs for Avionics Systems

1. Introduction

Dr. I. J. Gabelman, Technical Associates

Advanced technology has made available to the NATO military commander an array of highly sophisticated, extremely complex systems which help him to reach his operational objectives. Acquiring this increased capability however has been costly; so costly that it presents a significant budgetary problem to the member nations of NATO. The Life Cycle Costs (LCC), defined as the total costs of acquiring, operating and supporting a system over its lifetime, has come under careful scrutiny. Methodology has been evolved which enables costs of current weapon systems to be reduced and costs of weapon systems now in development to be controlled.

The most visible costs are those associated with procurement, research and development, test and evaluation. These account for perhaps one-third of the total LCC. Operation and maintenance and manpower costs are roughly the other two-thirds. Cost reduction techniques can be applied by everyone who is involved and contributes to the fielding of a weapon system in any phase.

Life cycle costs can be lowered in many ways. In the development and acquisition phase of a system acquisition wherever possible objectives should be limited; wherever possible commercial products particularly those with high production-volume parts should be used; simple designs should be employed and the data required should be minimized.

Product reliability improvement decreases support costs in the field. While a great deal of research and development is taking place in the laboratories to improve product reliability there are several approaches that can be employed now to increase system reliability and decrease LCC. Simple proven designs should be used; production and quality control should be improved and more efficient development and test procedures employed.

In the area of logistic support, common support equipment should be used; standardization should be extensively employed; training and documentation should be improved and commercial resources used.

2. Lecture Series Summary

This two-day lecture series will introduce the most recent developments in life cycle cost methodology for avionics systems. The speakers represent Canada, the United Kingdom, and the United States, and will support their discussions with examples drawn from current experience in NATO nations in the application of life cycle cost programs on avionics systems.

Following are summaries of the presentations:

The Life Cycle Cost Concept - A Management Tool for Planning and Control	Dr. E. N. Dodson General Research, Corp., U.S.

Dr. Dodson will explore the life cycle cost concept as a management tool. He will discuss the principles upon which LCC rests and the procedures used in its implementation in the development and acquisition phase of system procurement. In particular, he will describe the elements of the design-to-cost program, the need for parametric cost estimating and other estimating techniques to cope with rapid technological change, and the elements of risk analysis.

Dr. Dodson will illustrate his discussions with examples drawn from data processing systems in avionics environments. These examples will be considered from the point of view of hardware and software.

The Development and Implementation of Life Cycle Cost Methodology	T. D. Kiang Bell-Northern Research, Canada

Mr. Kiang will discuss the methodology developed for the Canadian Department of National Defence for carrying out comparative engineering evaluations as an aid to management decision-making. This methodology is unique in that it relates the life cycle cost of a system to a system effectiveness parameter, namely availability. The generalized life cycle management cost model can analyse a system of one or more prime equipments situated at one or more locations, and takes into account the maintenance and logistics support provided. Applications of the model will be illustrated by examples from a study carried out on the Micro-Electronic Airborne TACAN equipment. Mr. Kiang will discuss the decision flow involved in implementing this LCC methodology in the Canadian defence environments, and will describe some of the implications and management problems in LCC implementation.

Recent Experience in the Application of LCC Models	Mr. J. J. Naresky Rome Air Development Center, U.S.

Mr. Naresky will describe recent experience in the application of some of the LCC models currently used in the U.S. military environment, including Acquisition LCC models and Operation and Logistics Support Models. He will present material from some recent RADC contracts concerning cost-estimating and relationships, LCC trade-offs, and RIW incentives. He will also discuss the derivation of confidence levels in estimating LCC costs.

Life Cycle Cost Producrement
In The UK

Mr. P. G. Reich
Ministry of Defence, U.K.

Mr. Reich will describe UK experience in the acquisition and procurement of avionics system using LCC methodology. He will cover the source selection and evaluation process in LCC procurement, and detail typical LCC contract provisions. Mr. Reich will discuss the significance of data requirements and data sources in LCC procurement, as well as data availability, interpretation, and applicability.

LIFE CYCLE COST ANALYSIS: CONCEPTS AND PROCEDURES

Edward N. Dodson
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SUMMARY

Limited budgets and the growing costs of high-technology have prompted great interest in cost estimation, a field in which General Research Corporation (GRC) has been deeply involved for over ten years. We have been particularly concerned with parametric estimating techniques--techniques which are most suitable during the early phases of an equipment's "life-cycle." GRC has conducted methodological studies for the Assistant Secretary of Defense, each of the armed services, the National Aeronautics and Space Administration, and a number of other government agencies.

This paper is drawn from these various studies and is intended as a basic exposition of the parametric method of cost analysis, especially as it applies to modern high-technology systems. Hopefully, the reader will find some well-founded and practical guidance to the estimation of costs for new systems.

1. INTRODUCTION

An evaluation of overall program costs and benefits is a fundamental element of good management. Such evaluations are required in order (1) to decide whether to undertake a particular program, (2) to choose among alternative program designs, and (3) to establish a specific project plan of resource commitments and anticipated returns. The general literature, and indeed the daily news, are replete with examples of projects for which the initial cost estimates proved to be grossly in error. In many instances programs afflicted with overruns have been cancelled after considerable expenditure; more often, quantities are cut back or performance is compromised. In either case there is a patent waste of valuable resources.

The parametric method of estimating costs is particularly well-suited for the early phases of a program's "life-cycle"--the time when comparatively few details about the eventual equipments are known, yet many of the important program decisions must be made. Both the General Accounting Office (GAO) and the Department of Defense (DoD) have indicated that by the time a system completes the Concept Formulation stage (DSARC I in DoD parlance) 70% of the life-cycle cost has been determined, i.e., has been fixed by the choices made to that point in the life cycle. By completion of the System Definition stage (DSARC II), 85% of the cost is determined.

A recent study[1] within the Department of Defense elaborates upon the merit of the parametric approach:*

> ...estimates for new weapon systems acquisition costs are either derived from detailed, grass root calculations (the industrial engineering approach) or based on relationships between more aggregated components of system cost and the physical and/or performance characteristics of the system. These relationships should be derived from cost histories on prior programs. The latter method is often called the parametric approach. It is clear that, during the early phases of the acquisition process, only limited design information is available and considerable uncertainty surrounds both this information and whatever planning data is available on how the new system will be developed and produced. Nonetheless, cost estimates must be made. Both the fact of limited and uncertain information on which to base estimates, and the use to be made of these cost estimates, strongly suggest the employment of parametric estimating procedures. The parametric approach is particularly suited to making estimates based on limited physical and performance information.
>
> For most new systems, the parametric approach is the only method that can be used to make an estimate from the limited information available during concept formulation, i.e., when only mission and performance envelopes are defined. Only subsequently when detailed contractor proposals are being prepared can the industrial engineering procedures be applied. Furthermore, parametric methods provide the analyst with an inexpensive means of examining the impact on cost of a variety of changes in system performance requirements--information of particular importance during the early phases of the development and planning processes.

In short, the parametric approach is based upon aggregate relationships between cost and the physical/performance characteristics of the system under study. These relationships are derived from related historical data, generally following the principles of statistical inference.

This paper outlines the general principles and procedures of parametric cost analysis. In doing so it draws upon a number of earlier reports and documents[2-7] representing studies conducted for many federal agencies. While most of these have been within the Department of Defense (including each of the services and various elements within the Office of the Secretary of Defense), we have also developed costing procedures and estimating-relationships for the Environmental Protection Agency, the Department of Housing and Urban Development, NASA, and others.

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*While many of the discussions and examples in this paper emphasize military systems, the methods and procedures are applicable to high-technology equipment in such diverse fields as transportation, commercial electronics, etc.

The discussions in this paper consider costs solely in terms of direct dollar outlays, ignoring social, environmental, and other costs external to the conventional measures of dollar costs (although the general principles are appropriate and have been applied to these and other factors).

Most of our illustrations concern the cost to the government of work done by contractors during the production phase of the material life cycle, reflecting thereby the actual emphasis (and state-of-the-art) in the cost analysis community. While the principles of statistical inference are applicable to other elements of costs, the difficulty of acquiring data and in establishing cost-determining relationships have limited the application of parametric techniques to phases such as Research and Development, and operation in the field.

In Sec. 2 the basic elements, or "steps," of parametric cost analysis are discussed and illustrated. While these steps are set forth in separate and sequential paragraphs, it should be emphasized that there are numerous interrelations and "feedback loops" among them (as illustrated in simplified form in Fig. 1.1). For example, one of the first steps entails developing a formally structured table of the individual cost elements to be considered. Ideally, the organization, detail, and definition of these cost elements could be set forth at the outset. In practice, however, such classifications often must be revised to reflect the format of the cost accounting information obtained during the data collection phase.

Similarly, the formulation of cost hypotheses and their statistical evaluations are often conducted in a series of iterative steps. Data collection, of course, is also closely interrelated with the formulation of hypotheses and the evaluation of Cost Estimating Relationships (CERs).

Section 3 discusses several refinements and extensions of parametric cost analysis.

2. PARAMETRIC COST ANALYSIS

2.1 Objectives, Scope, and Choice of Approach

The first step in parametric cost analysis (and any other analytic effort, for that matter) is to establish the objectives of the analysis and its scope. Three common objectives are:

1. To compare estimates of the total costs of a particular program with program benefits before deciding whether the program should be initiated.

2. To estimate total costs so that future budgets and financial requirements can be established.

3. To compare costs among competing alternatives.

While the analyst may of course be required to meet any <u>or all</u> of these objectives, each poses some distinctive analytic requirements. If the objective of the analysis is only to make cost comparisons among competing systems, its scope may be limited to estimating costs only for those items and characteristics which <u>differ</u> among the candidate systems. For other purposes, all the costs associated with the program(s) under study must be taken into account.*

Another distinction among these objectives pertains to the use of price-level indices. Cost-benefit analyses should be made in "constant" dollars (to the extent that benefits and costs are measured in dollars), while future budgetary planning normally requires "current" dollars.** In short, program evaluations are generally conducted in terms of <u>constant</u> dollars, while budgetary planning requires time-phasing of expenditures in <u>current</u> (or "then-Year") dollars.

Defining problem scope requires decisions as to the degree of <u>generality</u> desired, and this in turn touches upon the suitability of the parametric approach. By degree of generality we mean such questions as

> ...Is the analysis to provide estimating relationships for a <u>general</u> class of equipments (such as tactical missiles)? Or is the problem more narrowly defined (e.g., air-to-air tactical missiles, or air-to-air tactical missiles using radar guidance)? Or, is the estimate for a <u>specific</u> missile whose characteristics are fully defined?

If the task is to estimate costs of an item whose design is (1) specified in full detail, and (2) closely related to existing design and production techniques, the industrial engineering approach is probably the better choice to establish a definitive estimate. An independent parametric estimate may still be useful as a check of the more detailed estimate.

2.2 Cost Chart of Accounts

The next step in the analysis is to develop a formally structured table of the cost elements to be examined. The purpose of this "structure," called the Cost Chart of Accounts, is to ensure that (1) all costs are taken into account, (2) none are double-counted, and (3) individual cost elements are consistently and clearly defined. The Cost Chart of Accounts is a basic tool for organizing the analysis in keeping with its prescribed objectives and scope. The importance of this tool in defining the individual cost elements cannot be overstated; more often than not, differences in cost estimates stem from differences

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*There are several issues to be resolved in defining "all" of the costs; these are discussed in Sec. 2.2.

**Much of the debate about use of inflation indices seems to reflect a degree of confusion of these distinct objectives. "Constant" dollars represent costs expressed in terms of a specific year. Costs from other years ("current" dollars) are normalized to the base year (made "constant") by use of price indices (see discussion in Sec. 2.5).

in defining what is included in the estimate. For example, does hardware production cost include the costs of manufacturing engineering, quality control, or documentation? Are non-recurring costs allocated pro rata to the unit cost of hardware? Are autopilot costs included in missile guidance or in missile control? These representative issues are resolved in a carefully structured Chart of Accounts.

There are several ways to structure the Cost Chart of Accounts. At GRC we have generally used a straightforward, two-dimensional matrix.* One axis, called the Work Breakdown Structure, defines the "end items" (e.g., laser optics) while the second indicates various elements of the system life-cycle (e.g., initial tooling).

A Work Breakdown Structure is an organized array which identifies hardware, software, and services produced or performed during the life of a weapon system program. An example of a hardware item is a missile guidance system; an example of a service is system test and evaluation. The DoD document establishing criteria for the preparation and employment of work breakdown structures used in the acquisition of defense material items is Military Standard 881.[8] This document, intended for use by both contractors and DoD organizations, defines a WBS as:

> ...a product-oriented family tree composed of hardware, software, services, and other work tasks which result from project engineering efforts during the development and production of a defense material item, and which completely defines the product/program. A WBS displays and defines the product(s) to be developed or produces and relates the elements of work to be accomplished to each other and to the end product.

Again quoting from MIL-STD 881, the purpose of a WBS is to provide a framework that facilitates:

1. Effective management and technical base for planning and assigning management and technical responsibilities within government offices responsible for the acquisition of defense material items and contractors furnishing those items.

2. Consistent control and reporting of the progress and status of engineering and other contractor efforts throughout the development and production of defense material items.

Intended as a management planning and control device, it is not, therefore, necessarily intended to represent the best format for cost analyses. The WBS formats provided in MIL-STD 881 may be and often are modified by government and contractor organizations. Indeed, MIL STD 881 recognizes the need for flexibility in developing a WBS:

> When the prescribed elements and definitions are not applicable (because of an item's unique configuration, activities, or other requirements or when additional WBS element selection is needed or desired beyond the summary WBS) additional or substitute elements, properly defined,...may be used.

Variations in WBS format and in the definition of each item in the format tend to be a major problem to the cost analyst when working with historical data. These problems result from tailoring the WBS to contractor or government accounting systems or the needs of a particular program manager. Consequently, there may be as many formats and definitions as there are programs. Furthermore, there may be more than one WBS used in different reports for a single program depending on the purpose of the report or the level in the government/industry hierarchy at which the report is to be used.

Cost analysts who are concerned with new systems will generally be required to develop their own WBS formats. The organization of subsystems, equipments, and components should be chosen to reflect the general functional organization of the equipment under study. Table 2.1 illustrates the WBS developed in a recent GRC study of high-energy laser systems. This WBS also reflects some of the special requirements which characterize most cost studies. The laser study included a variety of laser types and modes of operation, and the WBS was devised to permit flexibility in system devices within the same WBS framework.**

Life Cycle Cost Categories

The second basic dimension of the Cost Chart of Accounts addresses the major phases of the "life cycle," i.e., the sequential activities in the history of a program which cover its inception through final

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*Some agencies use a three-dimensional accounting structure. One such structure includes (1) Areas of Activity, (2) Subdivisions of Work, and (3) Elements of Cost. Areas of Activity are the end-items, and thus correspond to the Work Breakdown Structure. Subdivisions of Work indicate the type of effort, such as Design, Management, Documentation, etc., while the Elements of Cost break-out the individual skills (technician, engineer) and cost categories of material, overhead, subcontract, etc.

In our two-dimensional matrix the Elements of Cost are not shown--the detail of types of labor and other resources are not broken-out separately. In general, the parametric method is not used to estimate costs at such a fine level of detail. Where necessary, some "rules-of-thumb" can be used to apportion aggregated costs among these detailed elements.

**The basic laser types included gas dynamic lasers, chemical lasers, and electric discharge lasers. The different operating modes included pulse or continuous-wave operation, and open- or closed-cycle operations. As far as the WBS is concerned, the difference among these alternatives is reflected by the inclusion or exclusion of particular elements. The basic WBS includes all elements which might be used; the cost analyst must choose those suitable for his particular problem.

replacement. The institutions and procedures which define these life cycle phases within the Defense Department and NASA have been evolving over the past several years. Current Defense Department procedures are summarized in Fig. 2.1. Basically they account for the following major phases, or cost categories:

Research and Development - This category includes those expenses which occur within the Validation and Full Scale Development Phases of the acquisition cycle. Included are all costs for the engineering design, analysis, development, and testing which are associated with the R&D effort directed to the elements of the Work Breakdown Structure. Normally these costs are funded from the RDTE Appropriation, but other appropriations* may be required to complete the R&D phase of the acquisition process.

Investment Non-Recurring - This category includes those non-recurring expenses necessary to acquire a production capability which are directed to the elements of the work breakdown structure. They are one-time expenses or capital investments and include the cost for Initial Production Facilities (IPF), as well as any other one-time cost associated with obtaining a production capability. Normally these costs are supported by the procurement appropriations, but other appropriations may be required within the investment phase of the acquisition process.

Investment Recurring - This category includes those expenses which are of a continuing nature in the production of a weapon/support system. It includes all costs for the Low Rate Initial Production (LRIP) and Full Scale Production (FSP) of the major system equipment, as well as the continuing expenses for the recurring investment effort directed to the elements of the Work Breakdown Structure. Normally these costs are supported by the procurement appropriations, but other appropriations (e.g., MPA in the Army) may be required in the investment phase of the acquisition process. Also included are the expenses incurred in delivering the weapon/support system or its components to its destination, all engineering changes, and modifications (a separate budget activity) occurring after acceptance but while the system is still in production.

Operating Cost - This category includes those expenses resulting from the operation, modification, maintenance, consumption, and disposal of materials and supplies for a weapon/support system after acceptance into the inventory.

There are both contractor and government ("in-house") costs in each of these life-cycle phases. Typically, the major efforts of development and production are undertaken by a contractor, with the government effort including management, some documentation and training activity, and various logistics activities. Within these broad categories there are numerous individual cost elements which account for specific activities within, say, R&D (see examples given in the horizontal axis of Table 2.1). The specific titles and meaning of these elements differ among the military services, NASA, and other agencies reflecting the different procedures which are followed in developing, producing, and operating various systems and equipments.

Government costs are generally estimated as a small percent of total contractor effort (based upon the argument that this management activity will scale with the overall magnitude of the contracted program). In some studies government costs are estimated as a "flat rate," e.g., $50,000 per year for maintaining a supply catalog.

Operating and Support are largely all-government costs (replenishment spares and some other expenditures may be contractor-incurred), and are seldom estimated with equations based upon performance or physical characteristics. While in principle they could be, the general practice is to rely upon manpower inputs from military commands, with maintenance, spares, modifications, and other O&S costs estimated as a factor of production costs. As the state-of-the-art in cost analysis improves, more of these O&S cost elements will be estimated parametrically.

Level of Disaggregation

As illustrated in Table 2.1, the Cost Chart of Accounts includes a hierarchy of detail, with successively finer levels of detail (or "levels of indenture") being defined within each major end-time and life cycle category. One issue to be resolved by the analyst is the level of detail at which individual cost-estimating relationships will be developed, i.e., the extent to which the systems and equipments are to be disaggregated. Several factors bear upon this decision:

- The objective of the analysis: If the goal of the analyst is to identify cost differences among individual components of a system, then he should do his work at a level of detail which is fine enough to reflect the distinctions among the components.

- The availability of data: The shortage of relevant data at a comparatively high level of detail often prompts a further disaggregation of the system under study in order to draw upon a wider base of analogous subsystems and components. To illustrate--consider the development of a CER for an airborne phased-array radar. There have been very few of these systems actually developed. However if the radar is disaggregated to a finer level of detail, such as antenna, transmitter, receiver, signal processor, power supply, etc., the analyst can take advantage of the fact that the transmitter, power supply, and other system elements are actually quite similar to other types of radars and--in many cases--to other equipments, such as communcations sets, ECM equipment, etc. This permits use of a larger data base with consequent improvements in accuracy.

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*"Appropriations" refer to the organization of budgetary accounts as they are enacted by the Congress. They represent a different means of classifying expenditures.

This process of disaggregation to draw upon a larger related data base requires special care and technical understanding on the part of the analyst to ensure that the "analogous subsystems" are truly relevant as far as the underlying determinants of cost are concerned. If his chosen analogs are really different in terms of the functional relationships with cost, then the cost model will be misspecified and the results will be erroneous.

- Major differences in uncertainty: one motivation for disaggregated estimates is to clearly identify key uncertainties. For example we have generally disaggregated array-radar estimates in order to isolate the uncertainties associated with phase-shifter costs. Similarly, it is desirable to disaggregate missile costs in order to separate the comparatively uncertain guidance estimates from the more confident estimates for propulsion and airframe.

- The potential for omitting key cost elements: one hazard of detailed or disaggregated cost elements is that significant integration and other system-level costs may be overlooked. The analyst must be careful to ensure that he has accounted for costs which may not be identifiable with particular subdivisions of the hardware, but which are nevertheless part of the overall system's cost. Thus, for example, there are various management and integration costs identified at the subsystem and system level in Table 2.1.

- Burdens upon the user: Another consequence of developing CERs at a highly disaggregated level of detail is a formidable number of individual estimating equations, and a resultant list of input parameters which may be impracticable for most users.

The ultimate level of detail is invariably a compromise among divergent considerations. It has been our experience that cost studies of high technology systems must be conducted at increasingly finer levels of detail. In this sense, the sharp distinctions between the parametric method and the "industrial engineering" approach are becoming much less pronounced.

The preceding steps have established a framework which defines the scope and detail of the analysis. As noted, the specific elements of the Cost Chart of Accounts are invariably modified as the analysis proceeds--largely because of the need to adapt the cost format to the availability of data. The next task of the analyst is to develop an estimating relationship for each element of the Chart of Accounts.

2.3 Formulating a Cost Hypothesis

The principle technique used in parametric cost analysis is that of statistical inference using the procedures of multiple regression. There are numerous texts which develop the rigorous principles and underlying theory of statistical inference (see e.g., Refs. 10-12). Particular emphasis should be given to the principle that a specific functional relationship between independent variables (cost "drivers") and a dependent variable (cost) should be hypothesized on the basis of a technical understanding of the process under study. Then, statistical procedures may be employed to verify the postulated CER.

In practice, however, statistical procedures are often used to <u>identify</u> the independent variables and to <u>specify</u> the functional form of the estimating equation. We feel this procedure is incorrect, although it is difficult to be absolutely rigorous on this point. Parametric cost analysis is often exploratory and there is invariably some trial-and-error in finding a defensible CER. Thus, a search (using statistical selection criteria) among a limited number of candidate hypotheses is not necessarily to be faulted. An understanding of the underlying relationships between dependent and independent variables may be achieved only after statistical indicators have pointed the way. But there must be an eventual logic and rationale for the engineering and economic relationships which underlie each CER. In short, the cost analyst must have an understanding of the process he is studying (e.g., development of a computer) which approaches the knowledge expected of an engineer.

Without this underlying logic, the CER can be very misleading, no matter how persuasive the statistical indicators may appear. Without insight and care, statistical procedures can be merely an organized way of going wrong with confidence.

With this preamble, the next step is the development of cost hypotheses (although, as noted, this step generally proceeds hand-in-hand with data collection and statistical evaluation).

In general, the analyst strives to identify a cause-and-effect relationship between selected independent and dependent variables. However, in practice, the actual relationship among the identified variables is often merely one of statistical correlation. Aside from spurious correlations, the dependent and "independent" variables may both be the effect of some common unidentified or unstated cause. For example, weight and input power are often observed to have high correlation with electronics costs and are used by some analysts as independent variables. In many cases these variables are common indicators of more basic causal factors (such as functional complexity).

For purposes of prediction this statistical association may be sufficient, i.e., the analyst need not establish an actual cause-and-effect relationship, as long as the same statistical relationship will be applicable in the forecast period (see discussion on the following page about "availability"). However the analyst should be aware of these relationships among the variables, and recognize that a different model must be developed for tradeoff analysis.

There are two main elements in the formulation of a CER: (1) selecting the candidate independent variables, or parameters of the CER, and (2) selecting a functional form for the CER. Each requires a sound understanding of the type of equipment and the process (such as R&D) which is under study. These substeps constitute the "art" of cost analysis.

2.3.1 Selecting Candidate Parameters

The objective of this sub-step is to identify which descriptive parameters are most likely to influence the particular cost being analyzed.[*] Typically, for production costs, the analyst will seek parameters which govern subsystem size or complexity. For example, transmitter power, computer speed, and antenna diameter are conventional parameters used in CERs for these respective subsystems. Other parameters which help explain variations in cost also may be identified; e.g., variations in cost for a given transmitter power would be expected as a function of frequency. These parameters may be further modified to reflect different design options, e.g., solid state versus tube designs.

This point prompts some additional comments about the identification of cost-determining parameters. The result of most systems analysis studies are expressed in terms of system performance measures, such as aircraft range, radar detection range, communcations bit rates.... It would be desirable to have cost relationships expressed in these same dimensions. However, to achieve various specified performance-levels, there are typically a number of design options, each of which impacts directly upon cost. These relationships between performance, design, and cost are summarized below:

$$\begin{tikzcd} & \text{Design \#1} \arrow[r, leftrightarrow] & \text{Cost \#1} \\ \text{Performance} \arrow[ur] \arrow[r] & \text{Design \#2} \arrow[r, leftrightarrow] & \text{Cost \#2} \\ & \vdots & \vdots \end{tikzcd}$$

With the passage of time, technological change can affect both the performance-design and design-cost relationships. For systems characterized by diverse and rapidly changing technologies, the use of a performance parameter in a cost equation incurs the risk of considerable variability. In these instances the analyst should carefully limit the performance-cost relationship to particular designs and technological choices (this point is discussed further in Sec. 3).

In this process of identifying the determinants of production cost, the analyst must draw heavily on his own technical skills plus those of knowledgeable people in the field. He must bear in mind that since major design problems are presumably resolved before production, any difficulty in figuring out how to design an article does not bear directly on the "complexity" of production (which is more affected by considerations of, say, machining tolerance, electronics interconnections, etc.).

Typically these same cost determinants are identified in CERs for research and development. The costs of fabricating an R&D Test article are generally correlated with the cost of the production article. However, design and some testing costs are more directly related to factors such as state-of-the-art advance; in short, to differences from the prevailing level of technology, rather than to absolute values of particular parameters. These points raise various methodological issues which we have addressed in a number of studies; they are discussed in more detail in Sec. 3.

Costs are also influenced by "program" variables, i.e., by characteristics not of the equipment but of the management philosophy and environment. For example, we have included variables within a CER to account for schedule considerations (was the schedule "normal" or "crash"?), and for differences in parts-screening and reliability-testing. Other program variables reflect differences in management structure and accounting procedures (Was development or system integration done within a government laboratory or by a private contractor?). In ongoing studies of computer software we find these program variables are highly significant.

One restriction in this process of identifying cost-determining parameters is that the parameters be "available." There are two aspects of this availability:

1. The parameter should be one which is specified early in the life cycle, and does not require completion of design before it is known. For example, the number of electronic components, or the weight and input-power requirement of electronics systems are generally not determined until the design is completed. Thus they are not useful as independent parameters in CERs which are to be used prior to design completion.[†]

2. The parameters should be easily and unambiguously measurable. To illustrate: recent airborne radar programs have emphasized advanced signal processing techniques (primarily for clutter processing and electronic countermeasures). Accounting for the use of particular techniques and for varying levels of system capability has proven to be extremely difficult. Moreover, because each system has proven to be virtually unique, a homogeneous data base cannot be developed.

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[*] Parameters such as the quantity procured and the level of inflation are discussed under Data Normalization (Sec. 2.5).

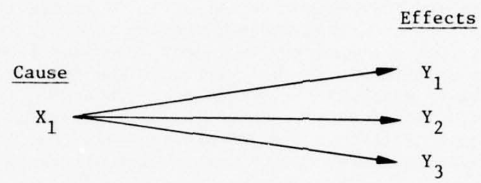
[†] For some applications, such as spacecraft avionics, weight and power are initial inputs in the form of design constraints. In these instances considerable care must be exercised: the data base should be restricted to those systems also developed under weight or power constraints.

As a consequence we have been forced to use cruder estimating parameters for radar receivers and signal processors (e.g., \$5,000 per receiver channel, or \$20,000 for a particular type of signal processing).

Similarly, missile accuracy has often been postulated as an explanatory variable for missile guidance costs. However, accuracy measures (CEP, etc.) for tactical missiles are seldom defined in consistent terms (Is it single-shot or salvo? Is the target maneuvering? At what speed and with what type of signature? How is distance from the target measured, etc?).

Where these criteria cannot be met, the analyst must use other parameters.

When no cause-and-effect relationships can be postulated, a common resort is to settle for a "mere" correlation with some measurable parameter. This point warrants elaboration. As noted previously, the cost analyst generally strives to identify a basic cause-and-effect relationship between independent and dependent variables. Hopefully, statistical procedures in conjunction with empirical data will establish that the dependent variable is indeed dependent. However, statistical correlations may actually reflect the fact that the dependent and "independent" variable(s) are--in reality--common effects of some other (generally unidentified) cause. Schematically, the relationship is illustrated below:



Y_1 and Y_2 may be strongly correlated through their common association with X_1. For purposes of predicting Y_2 it may be perfectly satisfactory to make use of this correlation--if Y_1 can be readily predicted. However, the analyst must bear in mind that direct analysis of the relationships between Y_1 and Y_2 (e.g., what would be the effect on Y_2 if Y_1 was purposely increased?) is generally infeasible.

Actual examples of these points are plentiful. For example, estimates of recurring production cost are often used to predict non-recurring investment cost. In fact, both costs are commonly influenced by system complexity and size. Electronics weight and power consumption are other common examples of a dependent parameter being used as an independent variable in cost analysis. Again, if these variables can be established by some other means, they can be used--with care--to estimate costs. However, direct tradeoffs between, say, cost and weight requires a different analytic approach.

2.3.2 Selecting a Functional Form of the CER

In this subtask the analyst hypothesizes a specific mathematical form for the estimating equation. For example, will the equation be of a simple linear form ($Y = A_0 + A_1 X_1 + A_2 X_2 + \ldots$)? Or logarithmic (e.g., $Y = A_0 + A_1 \log X_1 + \ldots$, or $\log Y = A_0 + A_1 \log X_1 + \ldots$)? Or, is the underlying relationship between dependent and independent variables such that a complicated mathematical expression should be used?

Perhaps the most basic choice is between linear and logarithmic forms. All too often the choice seems to be governed by the available supply of graph paper, or by the often misleading comparison of statistical indicators.* In fact, there is (or should be) a logic associated with this basic selection. The choice should be governed by the analyst's understanding of how costs vary with respect to changes in the independent parameters. Consider an example in which power output is the independent variable. A key question is: Do costs scale proportionately with power (i.e., an X percent change in power leads to a Y percent change in cost)? Or do cost and power relate in such a way that there is a constant cost per each unit variation in number of watts? Mathematically, the proporationate or logarithmic representation is $\frac{\Delta Y}{Y} \propto \frac{\Delta X}{X}$, while the linear representation is $\Delta Y \propto \Delta X$.† "Semi logarithmic" forms may also be specified in which one or another of the variables is expressed in logarithmic form.

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*There are a number of computer programs which provide regression statistics for a variety of candidate mathematical expressions. For many (if not most) of these the direct comparison of the Correlation Coefficient is misleading. The problem is that the residuals are not expressed in consistent terms (this point is discussed in Ref. 13).

†A corollary to this distinction between linear and logarithmic expressions is that the error terms in the statistical "models" which correspond to these two types of equation are different. The error in the linear function is assumed constant for all values pf the independent variable. It increases with larger values of this variable for the logarithmic form (see Ref. 14).

Analysts should also note that most curve-fitting procedures treat the linear and logarithmic forms differently--the former minimizes the absolute deviations while the latter minimizes proportionate deviations. The consequence of the difference is that statistical indicators for the two equation-forms cannot be directly compared.

The preceding discussion has dwelled upon the simplest of mathematical relationships between dependent and independent variables. Often, more complex equation forms are required. For example, in studies of electronics, RF frequency is a common independent variable. In analyzing the relationships between the cost of, say, radar preamplifiers or dish antennas and frequency, we have found two counteracting influences. On the one hand, higher frequencies (and correspondingly smaller wavelengths) mean smaller physical units, hence lower material costs. On the other hand, higher frequencies also mean more stringent control tolerances and corresponding higher costs. The combined effect of these two influences is a U-shaped function as illustrated in Fig. 2.2.

Statistical procedures can then be used to calibrate and verify the postulated functional form. These are discussed in Sec. 2.5, following a brief discussion of data collection and normalization.

2.4 Data Collection

The next step is the collection of relevant cost and technical data from historical projects which can be used to verify the postulated CER.* If creativity and technical insight are hallmarks of CER formulation, then tenacity and stamina are the watchwords of data collection. In virtually all cost analyses the fundamental limitation is the dearth of valid, consistently defined data, and most of the analyst's effort seems to be required for this phase of activity. Figure 2.3 is one analyst's view.

To compile data for the dependent and independent variables it is generally best to go where the data was originally generated, i.e., contractor accounting and engineering records. Care must be taken to ensure a full understanding of the data--What cost elements are included? Does the itemization of hardware elements correspond to the Work Breakdown Structure? In what year were the costs incurred? Are there any government-furnished equipments involved? What was the schedule of production items? Etc.?? Because of the perceived sensitivity of cost information, and because of the highly varied accounting systems in use throughout industry, the analyst can anticipate that a major share of his time and effort will be given to this phase of study. Hopefully the newly implemented CCDR system will alleviate these problems within the U.S. Department of Defense.

2.5 Data Normalization

Prior to incorporating data within the postulated estimating relationships the analyst must ensure that the data are consistently defined. This includes both technical and cost information. Normalization of technical data includes adjustments to ensure that, say, the specific impulse for various rocket motors is calculated at the same altitude, or that radar detection range is normalized to the same target cross-sectional area, number of pulses, false alarm probability, etc. In practice, the effort required to establish consistency in technical descriptors (independent variables) can be formidable.

Aside from uniform definitions of just what costs are included within the recorded expenditures, there are several considerations required to ensure that costs are displayed in consistent and comparable terms. These include the effects of (1) year-to-year price level changes, (2) productivity or manufacturing technology changes, (3) the "tiering" of contractors and subcontractors, and (4) "learning," or cost-quantity effects upon production costs.

Price-Level Changes. A conventional element in cost analysis is the normalization of cost data from different years to a "constant dollar" basis, thus ensuring comparability among the data and the derived CERs. DoD costing procedures call for cost estimates to be developed in terms of the fiscal year following the date of the study. Thus, cost estimates developed in January 1979 must be presented in FY 1980 dollars.†

In the United States the Office of Assistant Secretary of Defense (Comptroller) issues price level indices for use in weapons systems cost analysis; these are generally presented for Procurement and for RDTE, with a single index covering a broad variety of equipments and systems. The military services issue a somewhat more detailed set of price-level indices. For example, the Army provides separate indices for the following equipment and life-cycle categories:§

- Aircraft
- Weapons/track combat vehicles
- Missiles
- Electronics
- Ammunition-hardware
- OPA (Other Procurement, Army)
- RDTE (Research, Development, Test and Engineering)
- OMA (Operations and Maintenance, Army)
- MPA (Military Pay, Army)

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*To be most rigorous the analyst would limit his search to actual recorded costs. However, design studies and engineering estimates must often be used. Obviously, estimates are not as desirable as "actuals," but with reasonable care to ensure against, say, undue optimism in the interest of being low bidder, carefully developed estimates can be valuable.

†Price level indices are actually used for two purposes: (1) to normalize past data as part of the process of developing a CER and (2) to develop projections of future costs to "then-year" information for future budgetary planning.

§See AMCCP-ER memo, "Inflation Guidance," dated 10 December 1975.

The Air Force* makes forward projections for Airframe, Engine, and Avionics (for both Development and Production).

Associated with the use of these indices are several considerations which represent significant potential errors in cost analysis:

1. The additional detail for equipment categories and the periodic updating of price-level indices are largely restricted to future years. That is, they are addressed to the second objective of price-level normalization noted previously--projection of future costs to "then-year" information.

However, the first requirement of the cost analyst is an index to adjust costs from prior years to the base-line year of his estimates. Indices for prior years are not regularly updated, nor are revisions at finer levels of equipment detail directly issued.

2. Even with the most detailed indices there still is considerable variation among the constituent hardware elements (e.g., missile tail fins, fuel pumps, combustion chambers...) in terms of types of material and labor, and the relative mix of these two major inputs to the development and production process. In recent years, which have been characterized by sharp and varied price-level increases, the "averaging" within equipment catogories can mask considerable variability in actual price-level effects.

3. In practice, the available price level indices (which are based on labor and material inputs) are used to adjust the costs which have been recorded for particular subsystem and components. Thus, for example, the cost of a missile subsystem, which was incurred in--say--1973, is adjusted to 1977 dollars by multiplying the cost by a 1973-to-1977 index. But the analyst should note that the recorded cost of the missile subsystem is an output measure. It reflects the cost of individual inputs (labor, material...), together with the process by which inputs are combined, to yield the desired subsystem or component performance. If there is year-to-year variation in this process, another source of error may be introduced. This is amplified in the following discussion and in Sec. 3.

Productivity Changes. The price level indices discussed in the preceding paragraphs are used basically to account for changes in the unit prices of the inputs to R&D and production, i.e., in the prices of labor, material, equipment, etc. A related consideration is the effect of changes in manufacturing productivity, i.e., in the cost per unit output stemming from changes in the technology used in producing equipment. The most striking current example is probably in small computers and calculators, where the cost of a given level of computational capability has been dropping dramatically as new circuit technologies are implemented. These year-to-year changes in the cost per unit output are not captured by price level indices.

For many types of equipments these year-to-year changes in productivity are not pronounced. But, for some--notably avionics--they are, and data from programs more than a few years old should be used only with caution. Most cost analyses do not take these effects into account. Some methodological work to incorporate these changes is discussed in Sec. 3.

Contractor Tiering. Normalization of contractor tiering is another requirement to ensure that cost figures from different sources are comparable and consistently defined. In complex weapon systems, individual components of hardware are often marked up with G&A and profit through successive tiers of subcontractors and a final weapon system contractor. For example, small component suppliers (e.g., mirror manufacturers) sell their products to a subystem manufacturer (e.g., an optics subsystem supplier), who in turn sells the subsystem to a weapon system contractor. The prices quoted for a given component may differ markedly depending upon which tier is reporting.

One set of representative factors which account for the price differentials are illustrated in Table 2.2 (these factors are based upon studies of US Army systems, primarily SAFEGUARD). In studies of spacecraft avionics we have observed a different set of factors for NASA-sponsored programs, with an approximately 25% tiering factor at each stage.

"Learning," or Cost Quantity Relationships. A standard tool in analyzing the recurring costs of production items is the "learning curve." There is an extensive literature dealing with the principles and applications of this concept; the reader can find a complete discussion in Refs. 15 and 16.

In brief, the learning curve is a means of normalizing the effects of different total quantities upon the cost-per-unit. As originally conceived, the learning curve reflected the increased efficiency of labor (represented in terms of labor-hours per unit output) as more and more units are produced. In practice, learning curves are applied to the total recurring cost of production items. The effect of "learning" is portrayed as a decrease in (1) the cumulative average cost per unit as a function of quantity produced, or (2) the cost per unit of the most recent unit as a function of quantity. We have generally expressed the learning, or cost-quantity, relationship in terms of cumulative average cost per unit. The mathematical expression has the exponential form:

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*See Aeronautical Economic Escalation Indices, Comptroller, Aeronautical Systems Division, July 1975.

$$\text{Average cost per unit} = AX^{-b}$$

where A = first unit cost

X = quantity

b = an exponent, $0 < b < 1$, determined by the extent of learning*

Learning curves are used in two ways: (1) to normalize historical data so that variations in recorded costs due to differences in the quantity produced may be properly taken into account, and (2) to account for the effects of quantity-produced in equations set forth to estimate future costs.

The analysis of historical cost-quantity data is complicated by several factors. Costs for various quantities of output necessarily are recorded over a period of time, during which a number of other factors may influence unit cost. Notable among these are:

- Changes in overhead, General and Administrative expenses, and profit which may change in some systematic way over time and thus influence the unit cost.
- Changes in production rate. Most of the detailed industrial-engineering analyses we have seen have emphasized the importance of production rate in determining production cost. And yet, typically, production rate is not explicitly considered in cost analyses. If the rate changes markedly during an overall production run, there may be substantial effects upon unit production cost.
- Various modifications and engineering changes in the end product which often take place throughout a production run.
- Different contractual terms which may influence the recorded costs and/or actual efficiencies in the production process. One can readily imagine the influences from a shift to, say, a fixed-price-incentive contract from a cost-plus-fixed-fee contract.

In these circumstances, the analyst can only strive to identify these influences and adjust the data for, say, measured increases in overhead or cost due to modifications.

Even with careful accounting of these influences, there is considerable room for error in specifying actual values for learning curves (the learning rate for a given class of equipment may actually differ from contractor to contractor, and among different models of the same class). Thus it is prudent to select a "standard" quantity (to be used in comparing unit costs) that is actually within the actual range of available data. For example, if tactical missiles are being compared, and the range of actual quantities is between 100 and 1,000 units, then comparisons should be made for a standard quantity of, say, 500. Projection of data to a first-unit cost increases the possibility of error in the comparison.[16]

Calibrating and Verifying the CER

The preceding steps have identified the independent variables, postulated a specific mathematical form, and collected and normalized relevant data. The next task is to calibrate and verify the postulated CER using techniques of mathematical statistics. The procedure of least-squares curve-fitting, or multiple regression analysis, provide a rigorous and consistent means of determining a specific mathematical relationship. A full exposition of the underlying theory and principles of mathematical statistics and statistical inference is beyond the intended scope of this paper. Suffice it to say there are many texts which cover these topics (see, e.g., Refs. 10-12), and the analyst should understand the assumptions and limitations of this type of analysis. In practice, the rigorous requirements concerning the quantity and characteristics of the data are seldom fulfilled. However, the deviations and exceptions do not preclude the advantageous use of statistical procedures.

The results of a conventional regression analysis are (1) coefficients and exponents for the postulated mathematical form, and (2) a variety of statistical indicators which describe the relationship between the resultant mathematical relationship and the data in deriving it. Among the more useful indicators are the following (some additional discussion of these indicators is given in Appendix A):

- The Correlation Coefficient (R^2). The percent of variance in the dependent variable explained by the estimating function.
- The Standard Error of the Estimate. The standard deviation of the dependent variable from the computed values.
- t-statistics. For each coefficient, the ratio of the coefficient to its standard error.
- F-value. The ratio of the explained to unexplained variance, a measure of the significance of R^2.

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*The common measure of learning is expressed as the percent change in cost when the quantity is doubled. The value of b for a 90% learning curve is -0.152. To determine total cost, the unit cost expression is multiplied by the quantity. Thus, total cost = $AX^{(1-b)}$. It should be noted the "first unit cost" is a recurring cost; it is not the total cost of producing one item (which would include the costs of manufacturing engineering, tools, special test equipment, and other "non-recurring" items).

The correlation coefficient is a good general indicator, although it can be misleadingly high. The standard error of the estimate is an important indicator, although the proportionate (or percent) deviations are probably more illuminating. In fact, the analyst should examine the pattern of residuals ($Y_{actual} - Y_{estimate}$) for any systematic patterns (more on this subsequently).

The t-statistics for each coefficient should be high (>1) in order to have any confidence in the calculated values of the coefficient.*

There are numerous ways that these indicators can be deceptive (see, e.g., the discussion in Ref. 11). As a consequence, statistical indicators must be viewed with some caution. However, by ensuring that the data are reasonably well-distributed over the data space and that multi-collinearity and other potential statistical problems are reasonably well controlled, the analyst will find that these indicators can be a powerful tool.

With all these mathematical procedures, the ultimate criterion is the reasonableness of derived relationship. Do the relationships make sense in light of the analyst's knowledge about the system and about the data used in deriving the CER?

What to do if the CER is no Good

All too often the analyst will find that--at least for the first try--he has not developed a defensible estimating relationship. There are a number of potential explanations, and there are several recourses. Among the reasons why the estimating relationship (CER) is unsatisfactory may be:

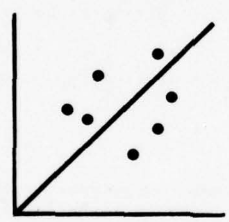
1. The analyst has failed to identify the actual cost-determining variables and the general nature of how these variables influence cost.

2. The data may be inaccurate or inadequate.

There are several things the analyst can do in order to address these problems:

1. *Reevaluate the identified independent variables*

The obvious (and most fundamental) recourse is to again think through the basic process under study (such as the production of a radar). Are there other factors which explain the costs of this process? As an aid in identifying these variables it is often useful to examine the pattern of residuals from the "unsuccessful" CER. To illustrate: the analyst can plot a graph showing actual cost versus estimated costs† using the CER.



Upon examination of those programs whose data lie consistently to one side of the 45° line (along which estimates = actuals), the analyst may find some single factor which stratifies the data in this same pattern. For example, in previous studies we have found stratifications based upon application area (airborne versus ground-based usage§), or differing levels of environmental or EMI specification, or a different design technology used in the design (e.g., with or without pulse frequency agility). In these instances the CER can be improved by addition of an appropriate dummy variable to stratify the data.

2. *Reevaluate the hypothesized mathematical form of the CER*

An originally hypothesized linear or log-linear mathematical form may not properly reflect the actual relationship between independent and dependent variables. Again an evaluation of the residuals from the "unsuccessful" CER may indicate a systematic pattern which is indicative of some heretofore-unrecognized relationship. For example, a systematic pattern of "actuals" exceeding estimates at the upper range of values may suggest that some upper bound of achievable performance is being approached. One might expect a functional relationship between performance and cost to be of the following form (which, in fact, we have observed):

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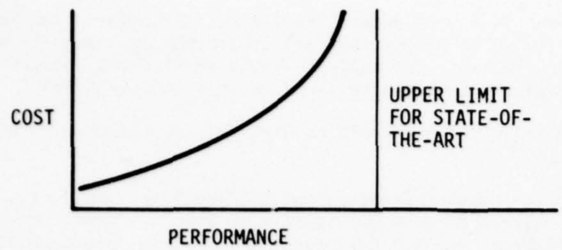
*There are a number of statistical problems which are commonly encountered; perhaps the most notable difficulty is multicollinearity (see Refs. 17, 18) which is generally manifested in low t-statistics although the correlation coefficient may be fairly high.

†I.e., cost derived by using actual values of the independent variables from programs in the data base as inputs to the estimating function.

§Different packaging and environmental specifications invariably lead to marked cost differences between these two operating regimes.



3. *Attempt to develop a CER at a different level of detail*

This procedure can be done either way, i.e., the analyst may seek relationships at a finer level of detail, or he may have to resort to a more aggregated relationship. As noted previously a finer level of detail may permit an expansion of the data base. At a finer level of detail there may be a broader selection of valid analogs. Thus there may be a larger sample of data with which to draw inferences about costs.

When additional data and/or analogs cannot be identified at a finer level of detail, the cost analyst may be forced to develop the CER at a higher level of aggregation, and to accept a less defensible estimating relationship. For example, in one study of spacecraft Stabilization and Control (S&C) subsystems, we found that each of the S&C subsystems for which we could obtain data was virtually unique. Each had a peculiar set of individual end-items (as indicated in Table 2.3), and we were unable to find other data which would permit development of CERs for each individual end-item. Consequently we were forced to develop an aggregated CER for the entire S&C subsystem--one which admittedly did not account for the distinct stabilization and control components.

4. *Settle for correlation with another variable which can be estimated*

As noted in an earlier discussion it is not always possible to establish a causal inference to explain variations in cost, and the analyst may have to settle for a simple correlation with another variable. One common example is the estimation of R&D costs for high-technology equipment as a function of the equipment production cost. Both are common effects of various facets of size and complexity. If a reasonably good CER is available for production cost, it can be used to estimate the value of the independent variable in the R&D CER.

Another example is the use of weight or input-power as independent variables in many electronics CERs.

5. *"Wait until next year"*

Finally, there will be occasions when no parametric estimating relationship can be found. Some elements of cost cannot be linked to any reasonably sized set of technical or program characteristics. One example was identified in a GRC study of "indirect" missile production costs such as manufacturing engineering, engineering changes, and documentation. Another category is Product Improvement, for which we were unable to establish any defensible CER (see, for example, the scatter of data points in Fig. 2.4). Upon further inquiry we found that Product Improvement expenditures were largely governed by the availability of "year-end" funds, i.e., they are subject to random quirks of the budget and not to the technical characteristics of the program itself. In short, there is no parametric relationship with respect to cost. The best we could do in this instance was to suggest an upper bound of a Product Improvement cost.

3. EXTENSIONS AND REFINEMENTS

3.1 Introduction

The preceding discussions have outlined the principles and procedures of parametric cost analysis. In this section various extensions and methodological refinements are discussed. For the most part they are extensions in the sense that they still follow the basic precepts of parametric cost analysis; they represent improved hypotheses and models of the process under study. They both address an issue which characterizes a significant share of the new equipment and systems which are acquired each year by private industry and the government, viz., the pervasive effects of technological change. Cost analysts have long incorporated the effects of major "jumps" in technology by developing separate CERs for, say, conventional tube vs. solid-state electronics, aluminum vs. titanium aircraft structures, metal vs. filament-wound rocket-motor cases, etc. However, cost analysts have generally not taken into account the continuous and fundamental way that technological change affects many areas of government and industry.

In research and development, technological change is a basic goal. In production, technological change directly affects the process of transforming inputs (resources) into outputs (delivered performance). Any analytic technique which purports to capture the basic elements which determine resource expenditures must include these effects. The "extensions" discussed in this section are exploratory and obviously incomplete. No doubt, they can be greatly refined and improved. Included are discussions of

- Procedures for measuring and incorporating state-of-the-art advance as a parameter in R&D cost-estimating relationships

- Procedures for incorporating effects of technological change in cost-estimating relationships for production systems.

3.2 Technological Change and R&D Programs

3.2.1 State-of-the-Art "Surfaces"

There are numerous studies focussing upon improved methods of estimating R&D costs which have identified state-of-the-art advance as a key cost determinant. Most of these studies have been based upon subjective assessments or rankings of this advance, or of some related consideration such as "complexity" (see, e.g., Refs. 19, 20).*

In a study conducted several years ago for the Assistant Secretary of Defense, we developed a quantitative approach to measuring advances in the state-of-the-art (SOA) based upon SOA "surfaces" for specific points in time. Our approach stems from several basic observations:

- The "state-of-the-art" (SOA) as a specific level of performance changes over time as new accomplishments are implemented and become part of the industry's general technical capabilities.

- At any particular point in time, the SOA for a particular system or application is a function of numerous parameters. For example, power output is one indicator of the SOA for a radar transmitter, but specification of a particular output in watts requires specific values or constraints upon other parameters such as frequency, weight, etc.

- Subsequent systems with greater capabilities advance the SOA, the advance being measurable in relation to the SOA prevailing at the time the design approach was selected.

Briefly, our procedure is to identify several variables which--to a reasonable degree--bound the state-of-the-art (SOA) in design achievement for the subsystem or equipment under study. These variables are generally performance and/or physical descriptors, and must be chosen so that they reflect actual design goals or constraints. A specific time period (e.g., late sixties) is then chosen, and all of the equipments developed in the period are cataloged in terms of the chosen technology variables. A "surface" is then fitted to the data for actual equipment, the surface being defined within the space described by the technology parameters.

To illustrate, in a study of avionics computers three technology variables were set forth as being representative of the computer state-of-the-art. A surface was fit to six data points representing six computers developed in the 1967-1968 time period, the results being illustrated in Fig. 3.1.† The advance implicit in any computer developed in the ensuing time period is then measurable. In effect this procedure is a quantitative, objective alternative to subjective qualitative assessments of "complexity" or "technological advance rating."§

While this approach is felt to be a valid and useful representation of technological change, it does have two fundamental limitations. First, in order to "fit" SOA surfaces for successive time frames, a considerable sample of data (i.e., number of different development items) is required. For some items, such as commercial computers, where there have been many development projects, this is no great problem. For most space and military systems, as well as other commercial equipment, there have been fewer development items which can be included in any one reasonably homogeneous set. Thus, there is insufficient data to specify a surface for each period of time. This drawback limits the usefulness of the approach for R&D costing of many high-technology systems.

A second limitation is that the time period for each surface is arbitrarily specified; thus the procedure lacks rigor in the sense that another analyst might specify a different time period--and will, in general, obtain different results. In short, two analysts working independently (and using the same data and technical parameters) may not come to the same analytic conclusions. As a result, our recent studies have focussed on variants of this overall approach which avoid these particular shortcomings.

3.2.2 Variants of the "Surface" Approach

There are several variants of this overall approach which permit economies in the size of the data sample, and avoid the arbitrary stipulation of time periods . . . all the while preserving the basic concept. One approach we have explored is to develop a more generalized equation for the surface in which

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*Still other studies have been concerned with measuring technological advance for purposes of technological forecasting (e.g., Ref. 21).

†The rationale and "mechanics" of this procedure are given in Ref. 22. An ellipsoidal form was used to account for the "diminishing returns" as increased values of any particular performance parameter are sought.

§This work, and its initial application to tactical missile propulsion and guidance has been fully documented in contract reports (Ref. 23) and in the open literature (Ref. 22, 24).

the equation's parameters are expressed as a function of time* (instead of "fitting" a specific surface to data for each individual time period). In the course of this work we identified related approaches which proved simpler to use. For example, Barr and Knight examined various forms of economic "productions functions" in an attempt to identify relationships which account for technological advance.[25] Among their investigations was a multiple regression analysis including various technical characteristics and calendar time. Alexander and Nelson of RAND[26] have set forth a related approach which we have implemented as follows:

- A limited number of technical characteristics, which (reasonably) encompass the technology of a particular class of subsystems, are set forth as independent variables in a multiple regression equation.
- The dependent variable is some consistently defined calendar milestone for each subsystem in the sample (such as completion of qualification test).
- The result of a multiple regression exercise is a function which can be interpreted as an expected date Y_e for achievement of a given set of technical characteristics (which have been specified as independent variables). Y_e is shown graphically in Fig. 3.2.
- The residuals $Y_e - Y_{actual}$ can be used as indicators of the extent to which each subsystem was "before its time," or may have lagged behind the average.† This is, in effect, a measure of relative technological advance.

An Illustration of the "Time Regression" Approach. One study which investigated the time regression approach focussed on general purpose avionics computers.[27] The following technical characteristics were set forth as indicators of technological capability, or state-of-the-art:

1. The speed of the computer in operations per second
2. The density of the central processing unit in pounds per cubic foot
3. The number of distinctive instruction types in the computer repertoire (add, shift left, etc.).

Technical data and the date of development completion were compiled for twenty-six airborne and space computers. They were then used in a multiple regression analysis to establish an equation which can be interpreted as the estimated, or expected, date of development-completion as a function of the three technology parameters. The resulting equation is

$$Y_E = 1961.3 + 0.03X_1 + 0.015X_2 + 0.06X_3 \qquad (3.1)$$

where Y_E = Expected year of development completion

X_1 = Number of distinct instruction types

X_2 = Number of operations (thousands) per second

X_3 = CPU density (lb/ft^3)

The next step was to examine the residuals, or deviations, of the actual data from the estimating function. These are illustrated in Fig. 3.3. The 26 computers are shown as they lie above and below the 45° line. A point above the line corresponds to an actual date of completion earlier than expected--in short, the computer was "ahead of its time." Conversely, computers falling below the line were "behind their time", i.e., on the basis of their technical performance capability they would have been expected to be through development at an earlier date. Thus, the residual, $(Y_E - Y_{ACTUAL})$, is interpretable as an indicator of state-of-the-art advance.

It is our hypothesis that extra development effort is required for a computer to be ahead of its time, and that being "behind the times" should be correlated with a reduced effort, i.e., it is hypothesized that the residual (or SOA advance) is positively correlated with development cost.

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*As shown in Fig. 3.1, the general equation for an ellipsoid is

$$\frac{X_1^2}{a_1^2} + \frac{X_2^2}{a_2^2} + \frac{X_3^2}{a_3^2} + \ldots = 1,$$

where the a_1, a_2, a_3 ... are the zero intercepts along the respective axes. We are examining a generalized form in which these intercepts are expressed in linear functions of time.

†We are imputing more to these residuals than is conveniently done in regression analysis. The usual assumption is that the dependent variable is represented by the estimating function, plus an error term which is represented by the pattern of residuals. In this particular approach it is assumed that there is information remaining in the pattern of residuals, in addition to the still-remaining error function.

This leads to the second step in this overall cost-estimating procedure, viz., incorporation of SOA advance in a cost-estimating relationship. The computers in the sample include both airborne and space computers. Typically, these two categories are fundamentally different in environmental specifications, reliability and test requirements, packaging, and other considerations. Thus the sample should be stratified.

The computer data base also includes another basic division: an older group of "hard-wired," synchronous computers, and a more recent set of synchronous, microprogrammable machines. This distinction is also hypothesized to have a significant impact upon cost.

These two classifications (represented as dichotomous, or dummy variables) were included with SOA advance in an estimating equation, with the following results:*

$$Y = 6.11 + 2.7\ X_1 - 4.7\ X_2 + 14.8\ X_3 \qquad (3.2)$$

where

Y = R&D cost (millions of 1974 dollars)

$X_1 = \Delta SOA$ (years)

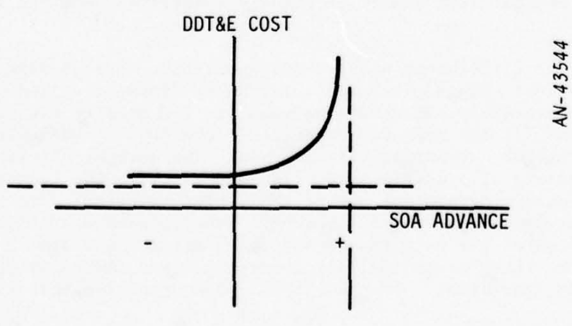
$X_2 =$ 1, for microprogrammable computers; 0, for synchronous computers

$X_3 =$ 1, for space computers; 0, for airborne computers

To use these procedures in evaluating a proposed new computer R&D effort, the analyst would observe the following steps:

- The individual technical characteristics of the proposed computer are inserted as X_1, X_2, and X_3 of Eq. 3.1. Y_e is calculated.
- The proposed date of R&D completion is used as Y_{ACTUAL}.
- $Y_e - Y_{ACTUAL}$ is calculated, and becomes X_1 in Eq. 3.2.
- Values of X_2 and X_3 in Eq. 3.2 are also specified for the proposed program.
- Using Eq. 3.2, calculate Y, the R&D cost.

Refinements of Resource-Estimating Equations. The simple linear relationship between R&D cost and state-of-the-art advance given in Eq. 3.2 is not altogether satisfactory, and in recent studies we have been refining it. First, there are various cost elements associated with R&D which are independent of SOA advance; thus a lower, or "fixed," cost will be approached as SOA advance diminishes. Similarly, there is an upper bound on achievable SOA-advance even though funds might be unlimited. Thus, one would expect a cost relationship asymptotic to some upper limit of SOA advance. In short, we hypothesize a complete functional form as follows:



We have examined several subsystems for which the span of available data did permit testing of this hypothesis. For example, cost estimating relationships have been developed in this form for communications multiplexers, traveling-wave tube amplifiers, and solid rocket motors.

*$R^2 = 0.7$, F-statistic = 8.6 (17 data points), t-statistics are 4.3, 1.4, and 3.3 respectively.

The Delta Performance Method. A complementary approach to measuring state-of-the-art advance is called "Delta Performance." While quite similar in principle to the time regression approach, the procedures of use differ in two respects:

- A separate relationship with time is developed for each individual technical parameter.
- Rather than using the entire sample of historical programs to establish an average level of technology as a function of time, the baseline level of technology (from which residuals are measured) is established from those programs in the sample which represent the most advanced capability.

A summary of this approach is given in Fig. 3.4.

The analysis begins with the specification of a summary set of performance or design characteristics which are considered indicative of the state of technology for the subsystem under study. A prerequisite for using the delta performance technique is that these characteristics be independent of one another in the sense that specifying a particular value of one characteristic does not require specifying values for the others. To illustrate, transmitter power per unit weight and receiver sensitivity are primary technology descriptors for transceivers; yet they are unrelated to one another in the sense that one does not act as a constraint on the other.

The available technical data are then examined to identify the "dominant" items over time (as illustrated in Fig. 3.4), and the particular development items which have the most advanced capability at each point in time are selected. These are used to develop a single-variable expression as a function of time.

For example, from a sample of 13 spacecraft transceivers, three were found to be dominant in terms of receiver sensitivity (Mariner IV achieved a sensitivity of -150 dBm in 1964; Mariner '69 set a new standard of -153 dBm in 1968, while the M-series transceiver achieved -154 dBm in 1975).

The dominant programs are then used in developing a regression relationship between the technology parameter and time. In the example of the spacecraft transceivers, the following expression was derived.

$$X_{E1} = 149 + 0.339\ (Y - 1960) \tag{3.3}$$

where X_{E1} = receiver sensitivity, -dBm

Y = calendar year

In effect, X_{E1} is an expected level of technology (in terms of receiver sensitivity) as a function of calendar time. Actual program values are measured as they fall above or below X_{E1} at any particular point in time. We hypothesize that the residuals ($X_{ACTUAL} - X_{E1}$), which represent indicators of state-of-the-art advance, are correlated with DDTE cost.

Other technology parameters are analyzed in a similar manner. The residuals from these analyses are then used as separate terms in a DDTE cost-estimating function.

Some Evaluative Remarks

There are a number of features common to each of these approaches, and each offers some distinctive characteristics. Each is based upon the assumption that technology can be represented in terms of physical or performance variables which are readily quantified. This is not always the case; for example, many special signal processing capabilities cannot be readily quantified, nor can special thrust control features of rocket engines.

There are some distinct differences among these approaches to measuring state-of-the-art in their representation of technological change over time. In the development of analytic models and estimating relationships, there are--invariably--tradeoffs between (1) the desired richness of detail used to describe the process under study, and (2) the need to economize in the use of available data which must be utilized in calibrating and verifying the estimating relationship. The several alternative approaches to measuring SOA advance represent a variety of specific tradeoffs between these two factors. As discussed previously, several of the approaches permit economical use of available historical data by incorporating the entire data sample in a "time regression" procedure. However, this economy is realized only by giving up some "richness" in the description of how performance variables change over time. In the time regression and delta performance procedures there is an implicit assumption that the relationships among the technology variables remain consistent over time.* In some fields of application this is not the case. In others,

*The regression equation of time as a function of one or more technology variables fixes the relationship among these various elements. However, in some technical fields these relationships change markedly over time. For example, some years ago there was a consistent effort to increase the power output of fire control radars. More recently, however, technical efforts have concentrated on other features in response to changes in operational requirements. We have noted comparable effects in studies of tactical rocket motors.

In our original "surface" approach, the SOA surfaces, which are defined for successive time intervals, need not move outward in any simple, consistent manner. Each surface can be positioned in any manner with respect to previous or subsequent surfaces, as may be indicated by actual technical progress.

there appears to be a "smoothness" in the implementation of technological developments for which these approaches may be well suited.

During these studies other "operational" considerations have come to light. As an example, the first step in the time-regression and delta performance procedures involves an equation in which various technical and performance characteristics are related to calendar time. With a properly selected set of characteristics, the inference is that the resulting estimating function depicts the time-changing capability to achieve particular performance levels. However, with another set of characteristics, the equation may reflect the time-changing nature of mission requirements, rather than technical capability. In this instance, the residuals (Y_E - Y_{ACTUAL}) would not be indicative of technological advance. They could merely indicate how individual systems came "before" or "after their time" in terms of changing mission requirements (or, in the case of commercial products, changing market demand).

To give a specific example: The overall size of computer memory is governed by mission goals, and does not represent a particular technological constraint. Use of this mission-determined parameter in the time regression procedure could lead to specious inferences about the technological advance represented in particular machines.*

To resolve this problem, variables should be chosen to reflect technological capability, not pure mission parameters. The variables should be given in terms of "efficiency measures," such as calculations per second, watts per pound, thrust per pound . . . , rather than "absolute-scale measures," such as total memory size, power output, thrust, etc. Efficiency measures represent general technological goals and constraints which are invariably being improved. The absolute-scale or size indicators are more directly a function of mission parameters, e.g., large missiles or computer memories are not indicative of technical capability as much as they reflect the requirements to meet operational objectives. Measures of changes over time in these parameters more often reflect changes in the various factors affecting operational requirements (e.g., military threat, stated goals in space exploration, business requirements in commercial systems, etc.). In these instances the residuals (Y_E - Y_{ACT}) cannot be interpreted as indicators of technological advance.

In some technical areas it has not been possible to characterize the state of technology with a reduced set of measurable parameters. Fire control radars and radar-guided missiles are prime examples; conventional measures, such as accuracy or range, do not represent major design goals in current systems. Rather, emphasis is being placed upon advanced signal processing capabilities, and other characteristics which are difficult to describe as scalar parameters. In this instance, our ability to account for technological change in R&D resource analysis is limited.

In the next section, technological change is discussed as it affects procurement costs.

3.3 MANUFACTURING TECHNOLOGY (OR PRODUCTIVITY) INDICES

3.3.1 Introduction

It is standard procedure in cost analysis to adjust recorded costs from different years to some constant-dollar basis, e.g., FY 1975 dollars. This adjustment--the price level index--normalizes for variations in the "purchasing power" of the dollar in obtaining the input factors (labor, material, etc.) of production or development.

For many equipments, notably electronics, there is need for an additional index--an "output index"--to normalize for year-to-year changes in manufacturing productivity, i.e., in the ability to produce a given level of output per unit cost. This point is amplified in the following paragraphs, with the argument being made that failure to account for these productivity changes is a source of the chronic errors in estimating electronics procurement costs.

3.3.2 A Productivity or Manufacturing Technology Index

In many application areas--most notably in digital computers and avionics--there have been remarkable and continuing advances in technology which impact directly upon the relationship between system performance and procurement cost. And yet, conventional cost analyses do not take these advances into account, an omission which can result in serious estimating error.

This is best explained by illustration. Consider the analyst faced with the problem of establishing a procurement cost-estimating relationship (CER) for computers. His task is to identify a functional relationship between computer performance (output) and the cost of producing that capability. He might hypothesize a CER based upon, for example, processing speed (millions of instructions per second, or MIPS). Then, historical cost and performance data are compiled and dollar figures are carefully adjusted to FY 75 dollars. However, the data from different years are not homogeneous in terms of the production technology underlying the performance-cost relationship. Early computer data would be based upon, say, 1969 production technology. More recent data would reflect a later technology, and the aggregation of these figures would mix time-varying effects of advances in production technology with the "cross sectional"

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*In addition to computers, this same problem has emerged in the analysis of TWT power amplifiers. This issue has also arisen in studies of other systems such as tactical missiles and fire control radars. For example, changes in mission parameters have prompted a shift from high-thrust rocket motors to longer sustained burning. Related to this change are reduced "torque" demands upon missile control subsystems. Several years ago there was considerable emphasis upon higher peak powers for airborne fire control radars. More recently, there has been a shift in emphasis to signal processing techniques.

In these examples, the time regression procedure--if used without an understanding of the interactions between missions requirements, technology, and performance--could be totally misleading.

relationship between specific performance levels and cost at a given point in time.*

Graphically, these relationships can be viewed in Fig. 3.5. If the analyst has three data points from 1969, 1971, and 1975, and does not normalize for the advance in technology, he may face the following difficulty: a plot of cost (properly normalized for price level changes) versus performance may look like Points 1, 2, and 3 (Fig. 3.5a). Extrapolation to some other 1975 equipment, with performance X_4, would lead to a cost estimate Y_4. However, the data are really "apples and oranges"--a mix of old and current technologies (as in Fig. 3.5b). To properly normalize for the advance in manufacturing technology, Points 1 and 2 must be adjusted to 1' and 2' to represent the cost of producing the 1969 and 1971 computers if they were actually produced in 1975. With proper adjustment, all the historical data would be placed along the same technology curve. The resulting cost estimate would be Y_4', given in 1975 dollars using 1975 technology.

To generalize from this example: There are numerous application areas characterized by (1) changes in design and in manufacturing technology which result in year-to-year reductions in cost per unit of output (system performance), and (2) operational requirements for continuing increases in performance. In these circumstances, the failure to account for manufacturing productivity changes represents a source of systematic bias (underestimation) in cost analysis.† To be sure, there are also many application areas where the pace of technological change--as it affects cost--is not particularly rapid, and historical data covering a span of years can be used without this productivity adjustment. But in specific fields, especially avionics, the need for normalization to a particular technology seems compelling. <u>A cost estimate is incomplete without specification of the applicable technology</u>.

Our initial inquiry into the use of productivity indices was in an analysis of avionics computers for the USAF Avionics Laboratory;[28] subsequently we have extended the investigation in a NASA-sponsored study of spacecraft avionics. In the computer study for the Air Force we reviewed the intensive literature indicating the rapid changes in computer productivity. Sharpe[29] depicted a number of relationships, as illustrated in Fig. 3.6. Turn[30] indicated the historical and projected data shown in Fig. 3.7. Seiler used data from a Bell Laboratories study in formulating a computer technology-cost index.[31]

One source from which we drew extensively was a study of computer indices developed for the Naval Air Development Center.[32] The NADC study is a comparatively detailed inquiry into prospective future technological developments in circuitry, components, etc. These are then combined into indices for future years from a base year of 1970; continued rapid improvements are forecast, as typified in Fig. 3.8. The index is multiplied by 1970 costs to establish costs using a future-year technology. (Note that the effect is to <u>reduce</u> estimated costs for, say, 1980; while the effect of the conventional price-level adjustment of 1980 dollars would be an <u>increase</u> in 1980 cost.) In developing a CER for avionics computers in 1974 technology and 1974 dollars, we first extended the indices back in time to span the historical data base. Historical costs were then adjusted to a 1974 technology and an appropriate CER was set forth. Not surprisingly, the difference in the estimating equations with and without this normalizing index was significant.

In more recent studies sponsored by NASA and by the U.S. Air Force, we have been examining procedures for deriving empirical measures for these technology indices. Our approach is to incorporate time (year of development completion) as an additional independent variable in a postulated CER. The regression coefficient for this new variable--derived from historical data--may be interpreted as the annual change in cost due to shifts in the estimating relationship.§

Several individual subsystems have been evaluated, including computers and communications subsystems. For example, in an analysis of procurement costs for avionics digital processing units, the following equation was derived:

$$\ell nC = 8.41 - .11\, X_1 + 0.249\, X_2 + 0.217\, \ell n\, X_3 + 0.274\, \ell n\, X_4 \qquad (3.4)$$

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*Careful analysts have recognized the pitfalls in trying to relate summary performance measures (such as MIPS) to cost without accounting for differences in design. But this accounting has generally been done in only a crude manner, e.g., stratifying for use of integrated circuits or discrete components. Most changes in technology seem more pervasive and consistently changing over time. Within electronic systems advances in solid-state circuitry have actually been implemented in a gradual ("smooth") manner over time so that the effects of these advances have been prolonged and continuous.

†In estimating the cost of a <u>reduced</u> performance system, there would be a tendency to <u>overestimate</u> the cost. The relationships in Fig. 3.5 are exaggerated to illustrate the impact of the index.

§To illustrate in terms of the simplified schematic of Fig. 3.5b--cost (Y) may be expressed as a function of MIPS (X) as follows:

$$Y = a + bX$$

However, the zero-intercept is a function of time: $a = a_0 - a_1 t$.

Substituting, we get $Y = a_0 - a_1 t + bX$. In this illustration, the equation becomes the new model, including both the general CER and the technology index.

where C = Cumulative average cost at $Q = 100$ in thousands of 1974 dollars

X_1 = Year of development completion - 1900

$$X_2 = \begin{cases} 0, & \text{if microprogrammable} \\ 1, & \text{if hard-wired, synchronous} \end{cases}$$

X_3 = [10^3 operations per second][word length, bits]

X_4 = Number of distinct instructions

The first variable is the explicit indicator of the year-by-year effect of advancing technology. Incorporating this indicator in the estimating equation properly accounts for this significant cost-determining factor and results in a more accurate portrayal of the relationships between cost and the other performance measures. The empirically derived technology indicator can be used to forecast future costs only with some assurance that historical trends will continue. The analyst may, of course, revise the coefficient in keeping with his own technological forecast.

Computers have exhibited the greatest year-to-year changes in manufacturing technology--as measured in terms of performance and cost. We have also examined other equipments such as transponders, antennas, multiplexers, and radar subsystems.

The preceding discussions have touched upon several of the methodological refinements we have been investigating in the past few years. This work is obviously incomplete and can undoubtedly be refined with additional effort. While these "mechanics" of accounting for technological advance are "experimental" we remain firmly convinced that the underlying phenomena of technological change and its impact on cost are very real and must be reflected in parametric cost analyses.

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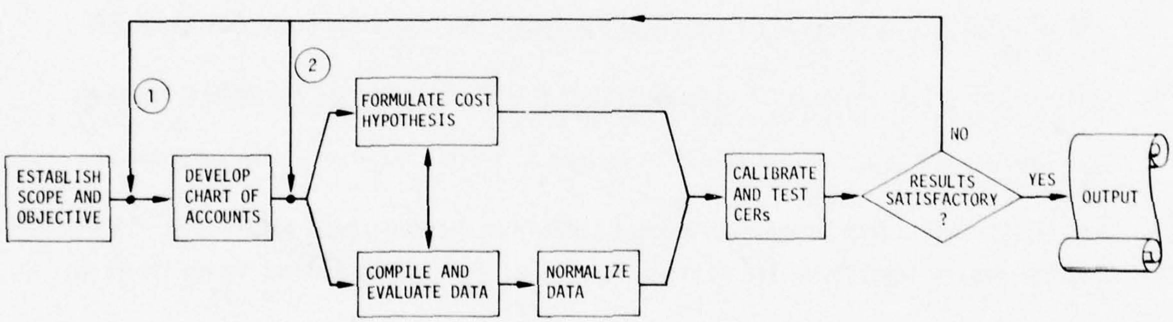
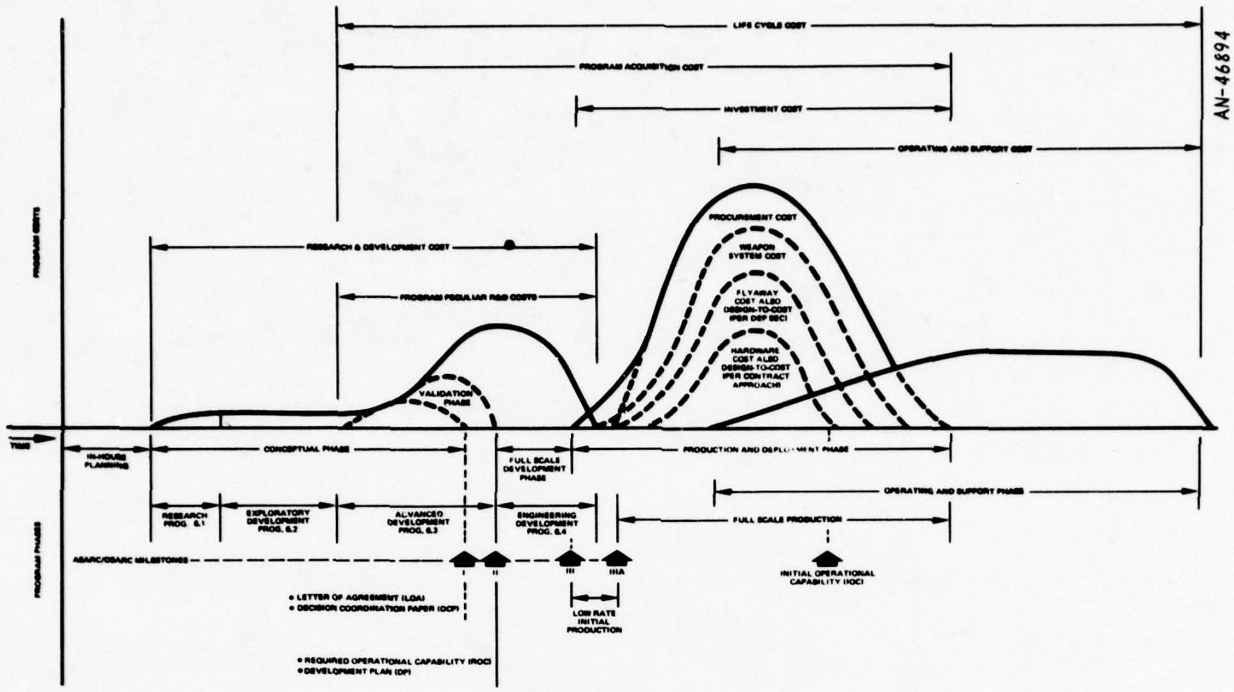


1 IF RESULTS UNSATISFACTORY, POSSIBLE REVISION OF LEVEL OF DETAIL

2 IF RESULTS UNSATISFACTORY, REVISION OF HYPOTHESES AND COLLECTION OF ADDITIONAL DATA

Figure 1.1. Schematic of Cost Analysis Procedures



SOURCE: US ARMY

Figure 2.1. Life Cycle of a Weapon System

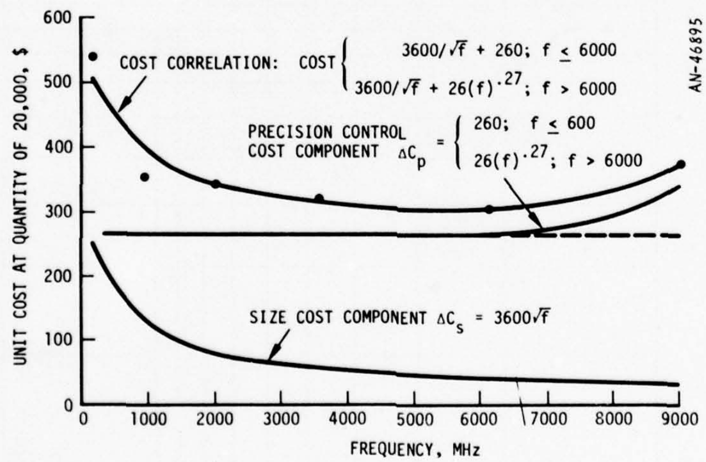


Figure 2.2. Receiver Preamplifier Cost Versus Frequency

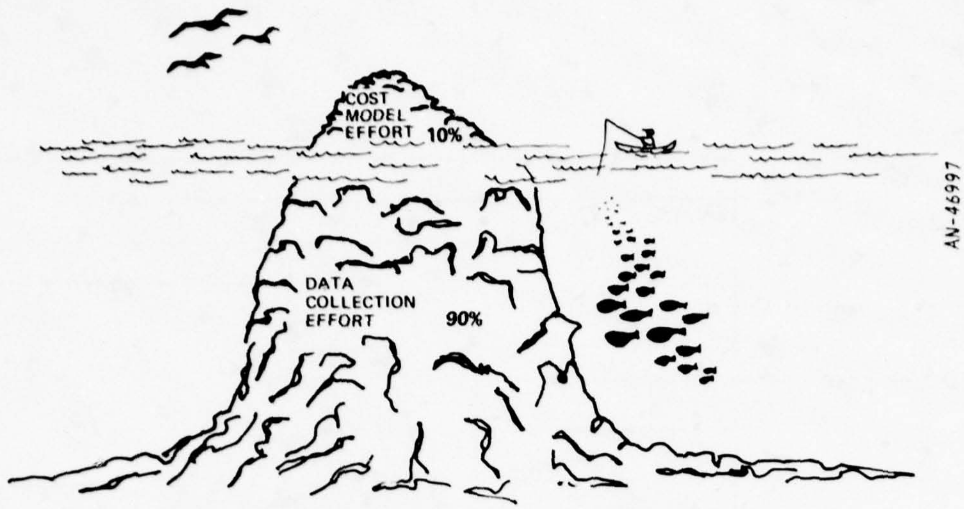


Figure 2.3. One Analyst's View of Cost Analysis Activities

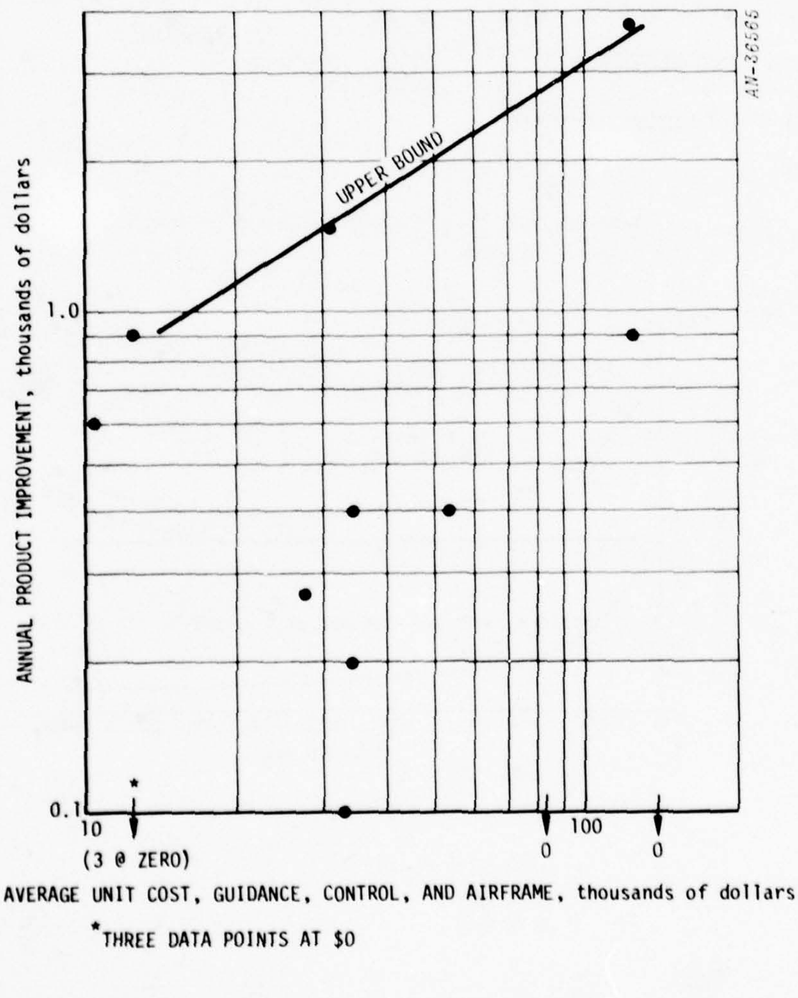
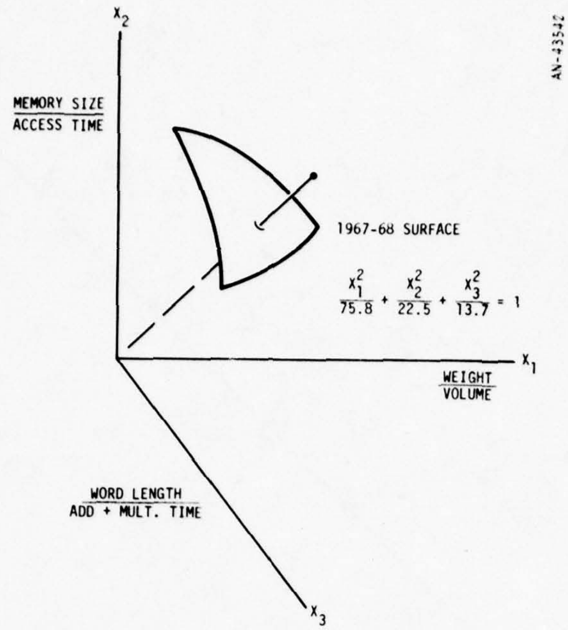


Figure 2.4. Product Improvement CER



COMPUTERS DEFINING A 1967-8 SURFACE	1969-70 COMPUTERS: SOA ADVANCE	
IBM - TC-2	CDC 5400 B	3.1
CP-2	469	0.275
UNIVAC 1818	IBM AP-1	0.341
GPK 20	CP-3	-0.04
NOR NDC-1060	EP/MP	5.37
LITTON L-3040		

Figure 3.1. State-of-the-Art Surface and Advance, Computers

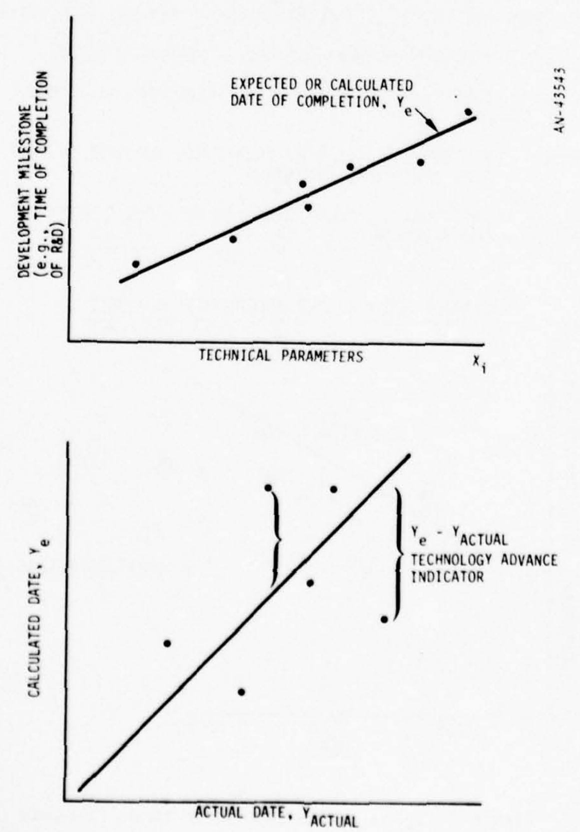


Figure 3.2. Derivation of Technology

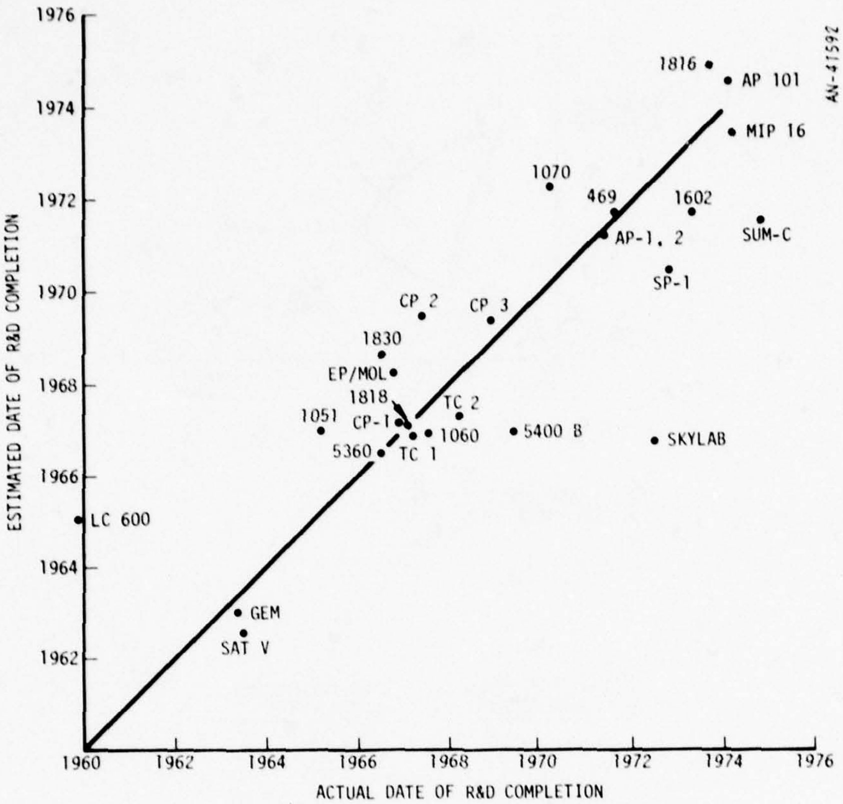


Figure 3.3. Actual Versus Estimated Completion Date for Avionics Computers

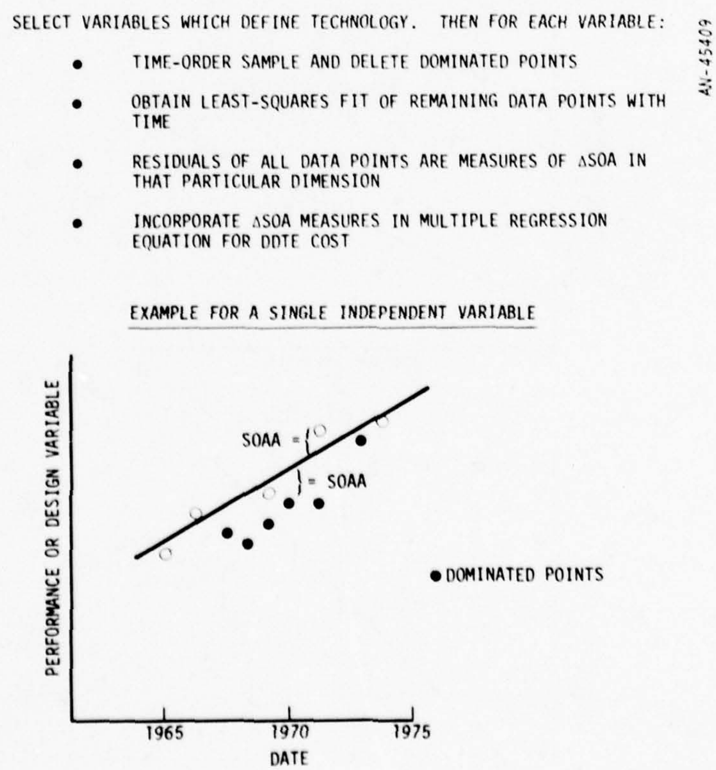


Figure 3.4. Delta Performance Method: Summary

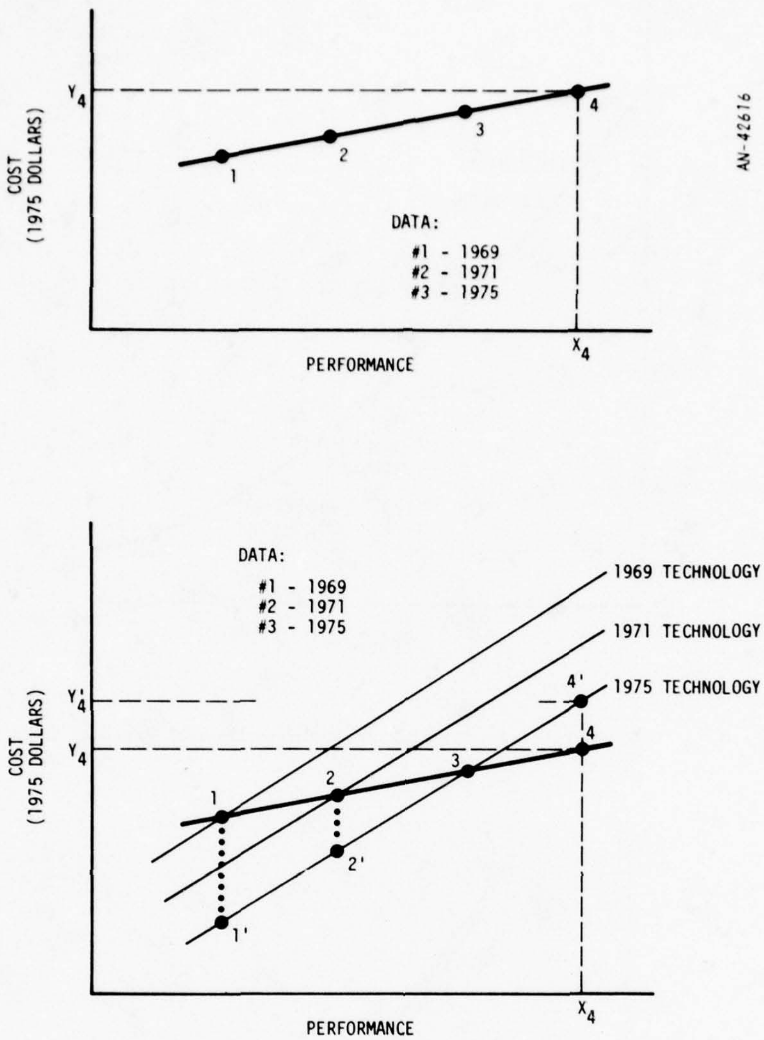


Figure 3.5. Cost/Performance Relationships

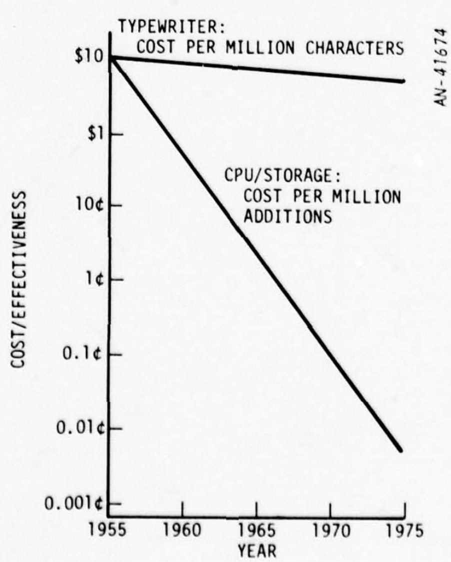


Figure 3.6. Estimated Trends in Computer Cost/Effectiveness

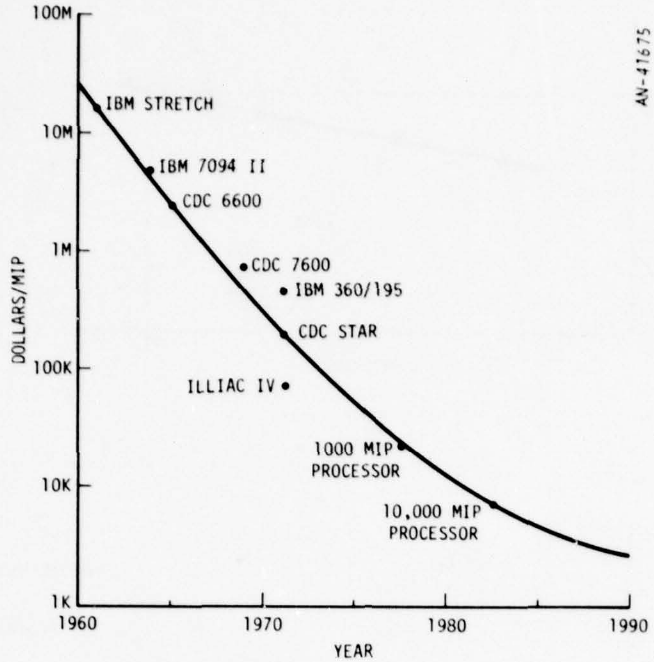


Figure 3.7. Cost Projections for High-Performance General-Purpose Computers

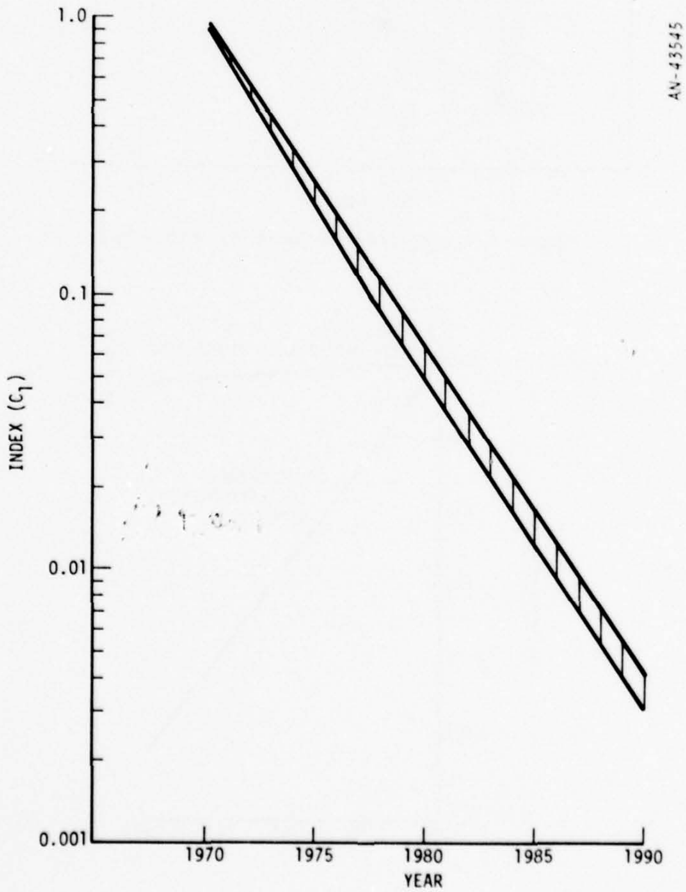


Figure 3.8. NADC Computer Hardware Cost Index

TABLE 2.1

COST CHART-OF-ACCOUNTS

		1 RDT&E	1.1 Adv. Dev.	Contractor	Design	Fab & Test	Other	Gov't.	1.2 Eng. Dev.	Contractor	Design	Fab & Test	Other	Gov't.	2 INVESTMENT	2.1 Non-Recurring	Contractor	Adv. Prod'n Engrg.	Initial Tooling	Other	Gov't.	2.2 Recurring	Contractor	Oper'l Equipment	Initial Spares	Related Support	Gov't.	3 O&S	3.1 Spares & Mods	3.2 Other Material	POL & VEH	Mun. Trng.	3.3 Personnel & Related	PPE & BOX/RPM	Med & Misc. Spt.	Pipeline	3.4 Maintenance
1	MISSION EQUIPMENT																																				
1.1	Device Subsystem																																				
1.1.1	Laser Device																																				
1.1.1.1	Thermal/Chemical Assembly																																				
	Combustion Chamber																																				
	CNM																																				
1.1.1.2	E-beam Gun																																				
1.1.2	Exhaust																																				
1.1.2.1	Disposal Assembly																																				
	Diffuser																																				
	Heat Exchanger																																				
	Ejector																																				
	Scrubber/Condenser																																				
	Ducting																																				
1.1.2.2	Recycling Assembly																																				
	Diffuser																																				
	Heat Exchanger																																				
	Compressor																																				
	Ducting																																				
1.1.3	Structures																																				
1.1.3.1	Optical Bench																																				
1.1.3.2	Other																																				
1.2	Fluids Subsystem																																				
1.2.1	Supply Equipment																																				
1.2.1.1	Tankage & Plumbing																																				
1.2.1.2	Valves & Control System																																				
1.2.1.3	Heater																																				
1.2.1.4	Pumps																																				
1.2.1.5	Other																																				
1.2.2.2	Fluids																																				
1.3	Auxiliary Power Subsystem																																				
1.3.1	Supply																																				
1.3.2	Conditioning																																				
1.4	Optics, Pointing & Tracking Subsystem																																				
1.4.1	Beam Optics & Alignment																																				
1.4.1.1	Cavity Optics																																				
1.4.1.2	Aero Window																																				
1.4.1.3	Beam Relay																																				
1.4.1.4	Auto Alignment																																				
1.4.2	Beam Pointing																																				
1.4.2.1	Turret, Shroud & Pointing																																				
1.4.2.2	Window																																				
1.4.2.3	Beam Expander																																				
1.4.3	Tracking																																				
1.4.3.1	Tracker/Imager																																				
1.4.3.2	Computer																																				
1.4.4	Ancillary																																				
1.4.4.1	Coolant																																				
1.4.4.2	Test & Prealignment																																				
1.5	Fire Control																																				
1.5.1	ACQ/Track Sensors																																				
	Radar																																				
	RFWR																																				
	IR/EO																																				
	Other																																				
	Laser Radar																																				
1.5.2	Data Processing																																				
1.5.3	Controls & Displays																																				
1.5.4	Other																																				
1.6	Subsystem Integration																																				
2	AEROSPACE GROUND EQUIPMENT																																				
2.1	Laser																																				
2.2	Fluids																																				
2.3	P&T																																				
2.4	Avionics																																				
2.5	Other																																				
3	PLATFORM																																				
3.1	Ground Facilities																																				
3.2	Aircraft																																				
	Basic Aircraft																																				
	Mod's																																				
3.3	Satellite																																				
	Satellite																																				
	Booster																																				
4	BASE FACILITIES																																				

TABLE 2.2

MODEL FOR MULTI-TIER SUBCONTRACTING

Contract Tier	Type of Input	Purchase Cost	MARK-UP FACTORS ASSUMED IN MODEL		
			G&A	Fee	Selling Price
Third	**Hardware components, subsystems**	**-**	**-**	**-**	**X**
Second	**Hardware subsystems, systems**	**X**	**0.20 (1.20X)**	**0.10 (1.32X)**	**1.32X = Y**
First	**Integrated hardware/**	**Y**	**0.08 (1.08Y)**	**0.02 (1.10Y)**	**1.10Y (1.45X)**

TABLE 2.3

STABILIZATION AND CONTROL END ITEMS

END ITEMS \ SPACECRAFT	Apollo Blk I	Apollo Blk II	L.M.	Gemini	Mariner	Pioneer F/G	OSO I	DSCS II	VELA	ATS A/E	OGO
Rate Gyro Package	X	X	X	X			X				
Attitude Gyro and Accelerometer Package	X										
Electronic Control Assemblies	X	X	X	X	X	X	X				
Attitude Translation Electronics			X								
Thermst/Translation Control			X								
Attitude Control Assembly			X								
Despin Electronics							X	X			
Control Timing								X			
Valve Driver Assembly								X			
Controls Converter								X			
Thrust Vector Servo		X									
Gimbal Driver Actuator			X								
Descent Engine Control Assembly			X								
Power Inverter				X							
Inertial Reference Unit					X						
Scan Actuator					X						
Reaction Control Assembly					X						
Magnetic Torquer							X				
Despin Mechanism								X			
Nutation Damper								X			
Optical Sensors						X		X			
Other Subsystem Related						X	X	X	X	X	X

THE DEVELOPMENT AND IMPLEMENTATION OF LIFE CYCLE COST METHODOLOGY

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SUMMARY

Bell-Northern Research has developed a life cycle cost methodology suitable for the Canadian Forces environments. The methodology will be used to implement the life cycle management system established by the Canadian Forces Procedure CFP 113. This paper describes the concept of the life cycle management system and the life cycle costing process. The unique features of the life cycle management cost model and its capability to relate cost and system effectiveness factors are discussed. The results of the model application to the AN/ARN-504 microtacan are presented.

1. INTRODUCTION

The concept of life cycle management system (LCMS) was initiated in 1973 within the Canadian Department of National Defence (DND) in response to the development of a comprehensive defence program management system (DPMS). The DPMS is aimed at providing guidelines for managing the defence services program which identifies current and future defence resource requirements. The LCMS complements the DPMS by providing an integrated approach for the management of materiel based on a life cycle concept. The LCMS calls for the development of a methodology suitable for DND life cycle resource evaluation and analysis.

In April 1976, Bell-Northern Research (BNR) was awarded a two-year development contract by DND. The contract was divided into two parts. The first, completed in April 1977, involved the development of life cycle cost (LCC) methodology. In the second part, a life cycle management cost model (hereafter designated as DND LCC model) was constructed by establishing the relationship between cost and system effectiveness factors. The model was validated for practical application using the microtacan - an airborne electronic navigation system carried on most of the aircraft in the Canadian Armed Forces. The result of this demonstration has presented DND with a powerful tool for comparative engineering evaluation in aid of management decision-making. The methodology will help life cycle materiel managers within the Canadian Forces environments in the procurement of new systems, for optimization studies on maintenance, and for logistics support plans for existing systems.

Before the details of the DND LCC model are presented, the intent and concept of the LCMS are briefly discussed to provide the background scenario for this unique Canadian development in LCC methodology.

2. LIFE CYCLE MANAGEMENT SYSTEM

2.1 Life Cycle Management Concept

Life cycle management is a concept which provides for the management of all activities from the time a requirement for materiel is conceived until the materiel is disposed of. It is defined in the Canadian Forces Procedure CFP 113 [1] as "the effective management of all activities required to acquire and support materiel needed for operations, from the time of its initial conception to the time of its disposal".

The principle activities performed during the life cycle of an equipment or system are associated with design, evaluation, acquisition, installation, maintenance, support, modification and disposal. Other integral activities required to achieve total life cycle management are analysis of effectiveness and life costs.

Ideally it is desirable to have one manager, who can be held accountable, for an equipment or system throughout its life cycle. The length of the life cycle for most Canadian Forces materiel as well as the movement of personnel and changes of organizational structure within DND precludes the achievement of this ideal approach. It is, therefore, necessary to provide a comprehensive system within which life cycle management can be achieved.

The LCMS therefore encompasses and consolidates all individual life cycle management activities. It is designed to ensure that any activity undertaken is within stated policy, is based on all plans and decisions made previously, and recognizes future requirements. As the life cycle of an equipment or system spans a considerable length of time, it has been found advantageous to divide the activities into stages.

2.2 The Life Cycle Stages

Although the life cycle of an equipment or system can be divided into any number of stages, the following division has been adopted within DND:

(a) Conception;

(b) Acquisition;

(c) In-Service; and

(d) Disposal.

The conception stage encompasses all the activities which are necessary to develop and define a means of meeting a stated requirement. The acquisition stage encompasses those activities required to acquire, install, and provide future support for the equipment or system selected in the conception stage. The in-service stage is normally the longest and encompasses the activities directed at the maintenance, support, and modification of an equipment or system throughout its operational life. The disposal stage consolidates the activities required to remove the equipment or system and its supporting materiel or facilities from the Canadian Forces.

2.3 The Life Cycle Materiel Manager

The person responsible for coordinating the principle life cycle management activities within the LCMS stages is designated as a life cycle materiel manager. A life cycle materiel manager may be responsible for one or more systems, subsystems, or equipments of varying complexity; or he may be designated for the management of common item materiel. Figure 1 illustrates the relationship between life cycle materiel managers.

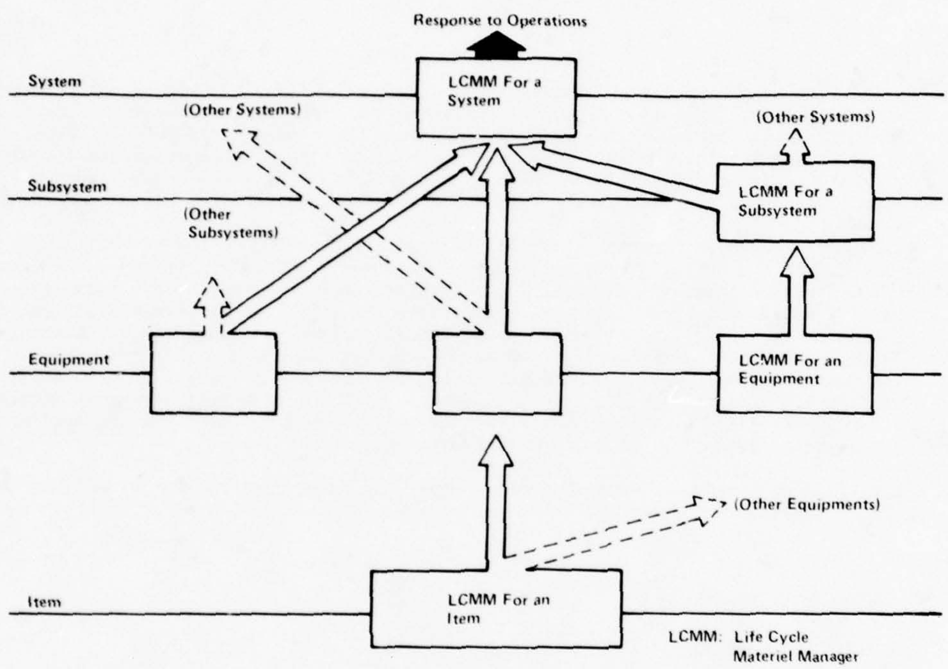

Figure 1 Relationship between Life Cycle Materiel Managers

2.4 Interface with Defence Program Management System

Figure 2 shows the interface between the LCMS and the DPMS.

The DPMS commences with the evaluation of a requirement and ends with the placing into service of a resource to satisfy that requirement. The DPMS provides a system for identifying a requirement in consonance with policy, developing broad optional means of satisfying the requirement, defining the needed resources, and obtaining approval to acquire those resources and placing them in service. To achieve this, the DPMS is structured into four phases:

(a) Policy Planning;

(b) Project Development;

(c) Project Definition; and

(d) Project Implementation.

Policy planning is the process of determining the goals of DND and describing the military capabilities required to meet them. Project development is determining in broad terms those means necessary and feasible to enable the Canadian Forces to achieve agreed levels of capability. Project definition is determining through detailed study and analysis the resources required to achieve project aims within imposed constraints.

The conception stage of the LCMS falls into the first three phases of the DPMS. The LCMS acquisition stage coincides with the DPMS implementation phase which is concerned with the implementation of the decisions arrived at the conclusion of project definition. The degree of responsibility and the extent

of participation in the two systems vary from project to project. However, once a project is approved, the LCMS takes over the prime responsibility to manage the resources through its in-service life and its disposal.

The LCMS provides the criteria for the development of the DND LCC model.

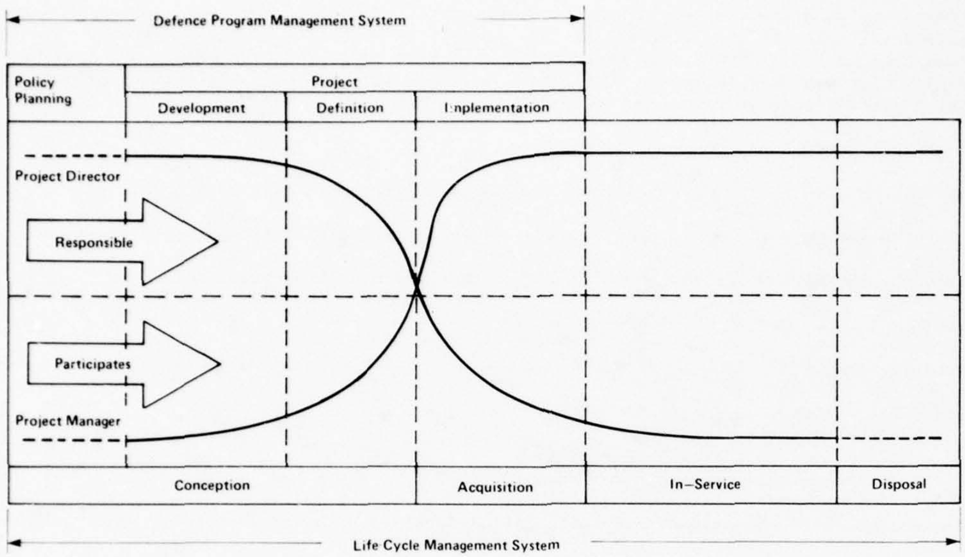

Figure 2 Interface between Life Cycle Management System and Defence Program Management System

3. LIFE CYCLE COST METHODOLOGY

3.1 Criteria for Model Development

The LCC methodology was developed primarily to meet the needs of DND. The baseline methodology was to provide a generalized model that relates cost and system effectiveness factors in quantitative terms. The following criteria were established for the development of the DND LCC model:

(a) The model must form a common starting point for LCC evaluations.

(b) The model must allow flexibility for the inclusion of additional cost contributing factors peculiar to an individual project.

(c) The model must allow flexibility for the deletion of cost elements that are not applicable in an individual project.

(d) The model must be constructed so that complex cost functions dependent on system effectiveness parameters (such as reliability, maintainability and logistics support) can be computed by a programmable facility.

(e) The model must provide for the adjustment of future expenses to a current dollar value on a specified annual discount rate.

Within this context, BNR has developed a model that determines optimum system values with respect to LCC and an important system effectiveness parameter, namely operational readiness. To permit clarification of the technical terms used in the model development, basic definitions were established.

3.2 Definitions

(a) Life Cycle Costing is the process of economic analysis to assess the total cost of ownership, taking into consideration the constraints associated with the system effectiveness requirements.

(b) Life Cycle Cost is defined as the sum of one-time initial costs incurred in the life cycle of an equipment or system prior to operation plus the ongoing costs incurred during its operating life.

(c) System Effectiveness is the probability that the system will provide, in terms of the resources

required, and as specified, either: (i) the maximum operational performance within the total cost prescribed, or (ii) the required value at the lowest total cost.

(d) Operational Readiness is the probability that, at any point in time, the system is either operating satisfactorily or ready to be placed in operation on demand, when used under stated conditions including allowable warning time. Thus, total calendar time is the basis for computation of operational readiness.

3.3 Objective Function of the Model

The DND LCC model is designed for comparative engineering studies in projects where trade-offs in life cycle resources of systems are possible and permissible. The model represents a set of mathematical expressions relating a general and flexible profile simulating real life system operation. Due to the non-linear and complex relationship that exists between system operational readiness and its LCC, a marginal allocation approach using Lagrange multipliers has been adopted for optimization purposes. This approach employs an interactive technique for optimal allocation of resources.

The objective function of the model is to:

(a) maximize system operational readiness for a given life cycle cost constraint, or

(b) minimize life cycle cost to meet a given system operational readiness requirement.

Mathematical expressions for the above objective function can be formulated as:

$$\text{Max } A_s\text{, subject to LCC} \leq C \quad (1)$$

$$\text{Min LCC, subject to } A_s \geq A \quad (2)$$

where A_s = System operational readiness
LCC = Life cycle cost
C = Life cycle cost constraint
A = System operational readiness target

Detailed mathematical expressions and their derivations are documented in a BNR report, Mathematical Model [2].

3.4 Model Structure

The structure of the DND LCC model is presented in Figure 3. The modular structure of the model provides flexibility in dealing with particular requirements of individual systems, and in performing different types of analyses.

Each block shown in Figure 3 represents an element of LCC or operational readiness. For convenience, the blocks are arranged in a set of numerical series. Blocks in the 100-series refer to elements of LCC; blocks in the 200-series refer to elements of operational readiness. Data requirements for each block are detailed in the LCC Methodology report [3].

The double arrows superimposed on the DND LCC model in Figure 3 indicate some of the more important relationships between cost elements and effectiveness elements; these arrows are not meant to be exhaustive for there are many more direct and indirect relationships.

The model is capable of dealing with any system that consists of one or more prime equipments that are situated at one or more locations; in addition, the model takes into account the maintenance and logistics support (MLS) system available to support the prime equipment.

To facilitate the computational process, mathematical expressions developed for the DND LCC model are programmed in Fortran IV using an IBM VM 370/168 computer system. The interactive feature of the computerized model permits rapid access to sensitivity analyses and parametric evaluations of LCC or operational readiness.

3.5 Computation of Operational Readiness

To compute operational readiness, a parameter of system effectiveness, the DND LCC model takes into account the operational readiness of all prime equipment associated with the system. In a system composed of several prime equipments, the prime equipment may be distributed over several locations. The problem is first considered location by location. For each location, the model computes the operational readiness of prime equipment at that location based on:

(a) factors peculiar to that location which contribute to operational readiness, and

(b) factors arising from the maintenance and logistics support system common to all locations.

Once the operational readiness of prime equipment at each location has been determined, the model can then compute overall system operational readiness, which is the prime system effectiveness parameter of concern in the DND LCC model.

The operational readiness of prime equipment at each location is computed as a function of mean uptime and mean downtime. The calculation of mean uptime takes into account mean-time-between-failures (MTBF), the utilization rate (i.e. ratio of operating hours to operable hours), the number of prime equipments in the system, and the mean-time-between-scheduled-maintenance (MTBSM). The calculation of mean downtime takes into account mean corrective maintenance time and mean scheduled maintenance time.

The greatest impact on the result is from the mean corrective maintenance time, which depends on the time needed for fault diagnosis and checkout, the time to replace the faulty item, administrative time, and supply delay time (i.e. the time required to obtain a spare item). Supply delay time depends upon the MLS system.

The model will compute supply delay time for each location of prime equipment. In addition, it can compute the optimum number and allocation of spares to be held at each location in the MLS system if these values have not been predetermined.

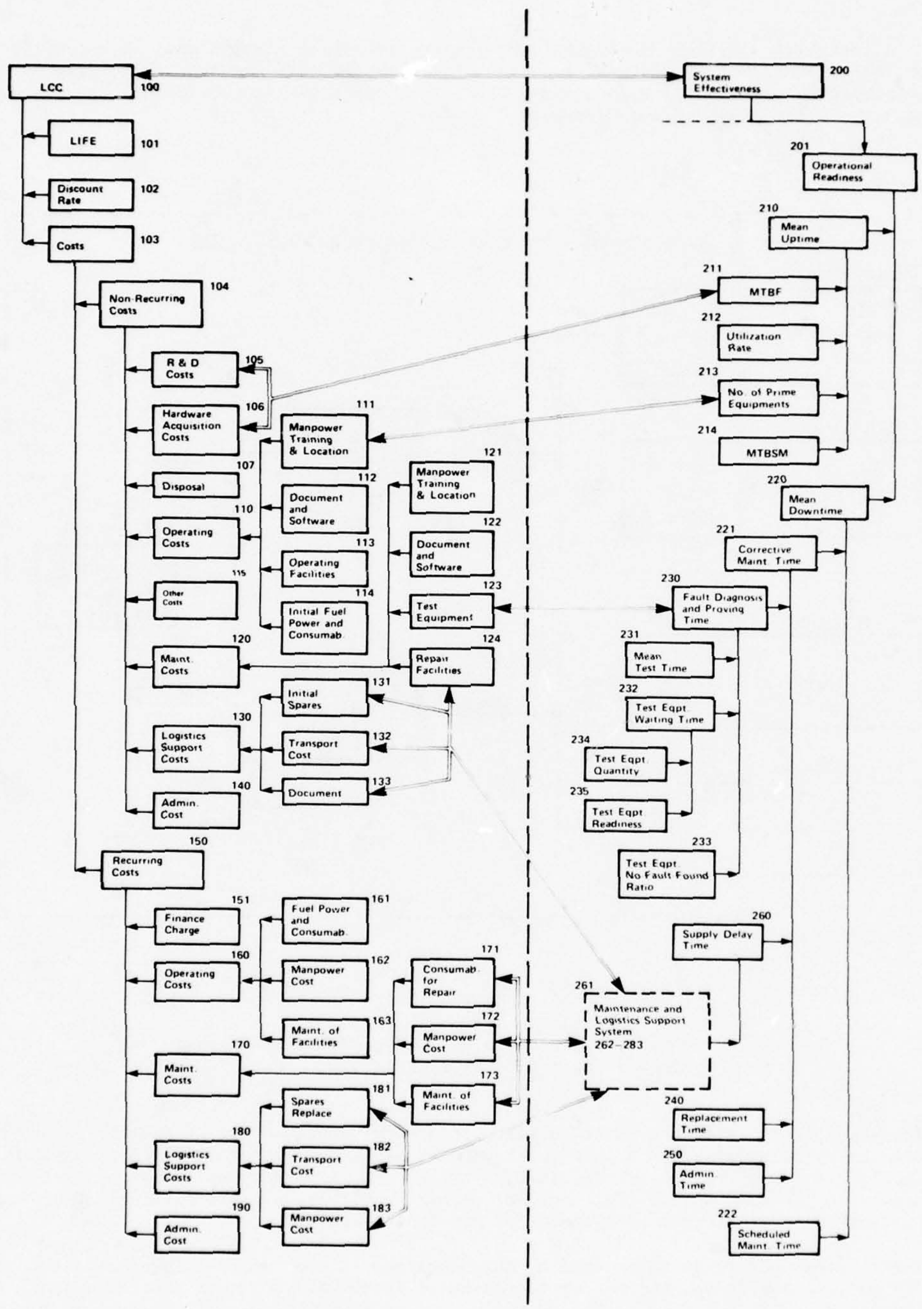

Figure 3 DND LCC Model

3.6 Maintenance and Logistics Support System

The DND LCC model makes detailed analysis of the maintenance and logistics support (MLS) system available to support the prime equipment. This MLS system encompasses all activity by the repair facilities and spares pools at various locations.

The many variables in the MLS system determine the time the prime equipment must wait for a spare (i.e. supply delay time, Block 260 of Figure 3). Thus, the MLS system affects downtime, and ultimately system operational readiness. In addition, possible changes in the MLS system to increase or reduce supply delay time will affect LCC.

The major portion of LCC often tends to be due to recurring costs during the in-service stage. Thus, LCC evaluations related to the MLS system can strongly influence LCC and achievable operational readiness. The problem is much more than a question of how many spares are needed for the initial procurement. The model can help to determine the effect on LCC and system operational readiness of decisions relating to: repair policies, number and type of test equipment to be used by repair facilities, manpower, etc.

Figure 4 illustrates a typical configuration of a comprehensive MLS system. At each prime equipment location, the failed equipment is restored back to service by the test and repair facility by replacing faulty line replaceable units (LRU) with a spare LRU. This spare LRU is provided by the MLS system. The faulty LRU is sent to the MLS system for repair.

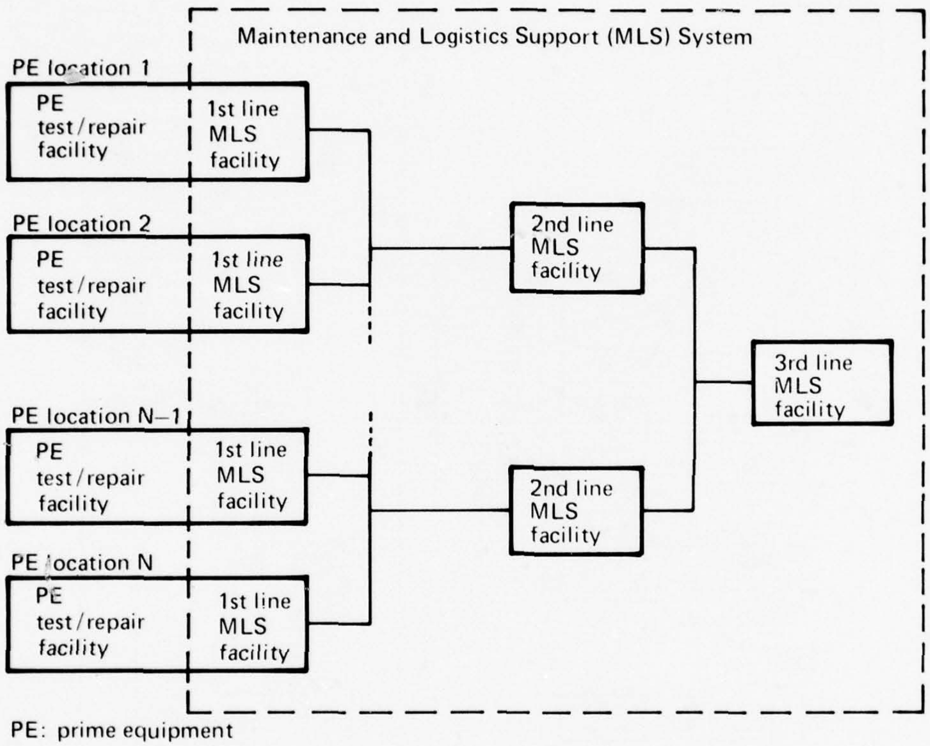

Figure 4 Typical Configuration of Comprehensive Maintenance and Logistics Support (MLS) System

The MLS system described in the model consists of at most three levels of facilities depending on the maintenance and support plan for a particular prime equipment. Each MLS facility consists of a test and repair facility and a spares pool. The test and repair facility and the spares pool need not necessarily be located at the same place. The test and repair facilities are dedicated to effecting repairs that cannot be performed at the preceding level of MLS facilities.

The general repair policy is determined by the hierarchy of the prime equipment and the cause of failure. This general repair/sparing policy incorporated in the DND LCC model for each level of the MLS system is summarized in Table 1. A typical operation of the MLS system is illustrated in Figure 5.

3.7 Computation of Life Cycle Cost

The model computes LCC as a function of non-recurring and recurring costs. Non-recurring or one-time costs include, where applicable: R&D, hardware acquisition, operations, maintenance, logistics support, administration, and disposal. Recurring costs, computed on an annual basis, include: finance charges, operations, maintenance, logistics support, and administration.

These costs are adjusted by a discount rate to convert the value of future dollars to present dollars and, if desired, to account for the effects of inflation. These calculations are extended over the expected lifetime of the system, or the period under study.

Table 1 Summary of Repair/Sparing Policy

Failed Item / Cause of Failure / Repair Action / Facility	Repair Policy						Sparing Policy		
Failed Item	PE	LRU		Module		Sub-Module	Spares Held		
Cause of Failure	Faulty LRU	Faulty Module (Type I)	Other Causes (Type II)	Faulty Sub-Mod. (Type I)	Other Causes (Type II)	All Causes	LRU	Module	Sub-Module
Repair Action	Replace LRU	Replace Module	Repair LRU	Replace Sub-Module	Repair Module	Discard			
PE Test/Repair Facility	X								
1st Line MLS Facility			X				X		
2nd Line MLS Facility		X	X		X		X	X	
3rd Line MLS Facility			X	X	X	X	X	X	X

Type I: Restoration of Failed Item Is Effected By Replacement of Lower Level Components

Type II: Restoration of Failed Item Is Effected By Repair of Item

PE: Prime Equipment

LRU: Line Replaceable Unit

3.8 Relationship Between System Effectiveness and LCC

The double arrows superimposed on the DND LCC model in Figure 3 indicate some of the more important relationships between cost elements and system effectiveness elements; these arrows are not meant to be exhaustive for there are many more direct and indirect relationships. The matrix of Table 2 provides a more comprehensive indication of some of the relationships that can exist between elements of LCC and elements of system effectiveness.

In general terms, system effectiveness can be improved or reduced by:

(a) decisions in R&D that influence system inherent reliability and maintainability, and

(b) decisions relating to the maintenance and logistics support provided to the system.

In both cases, decisions in (a) and (b) influence cost as well as system effectiveness. For example a decision to use high-reliability parts or to incorporate built-in-test equipment in the system should result in improved reliability and operational readiness; at the same time, these decisions will probably result in higher acquisition costs but may well produce lower overall costs over the life of the system.

Sensitivity studies can help identify those relationships in which small changes in input values have a significant effect on system effectiveness and LCC; thus efforts can be concentrated in these areas which have the greatest potential for cost savings and improved effectiveness. Sensitivity studies are performed by exercising the DND LCC model over a range of input values/decisions; in this way it may be found that some types of input data have a negligible effect on the model output over the range; other types of input can be identified where small changes in input produce substantial changes on the model output.

3.9 Assumptions

The LCC methodology developed for DND is generalized in nature. It is designed to accommodate most systems and equipments encountered in the Canadian Forces environments for LCC application. To meet such a broad scope of application, some assumptions are made and incorporated in the DND LCC model. The following summarizes these assumptions and limitations that are inherent in the model construction.

(a) All failures are random

Failures are assumed to follow a Poisson process. Where failures do not strictly follow a Poisson process, the model provides results that in most cases are within reasonable bounds for LCC and operational readiness. However, piecewise linear approximation has been used successfully to simulate wearout failure characteristics for all practical purposes.

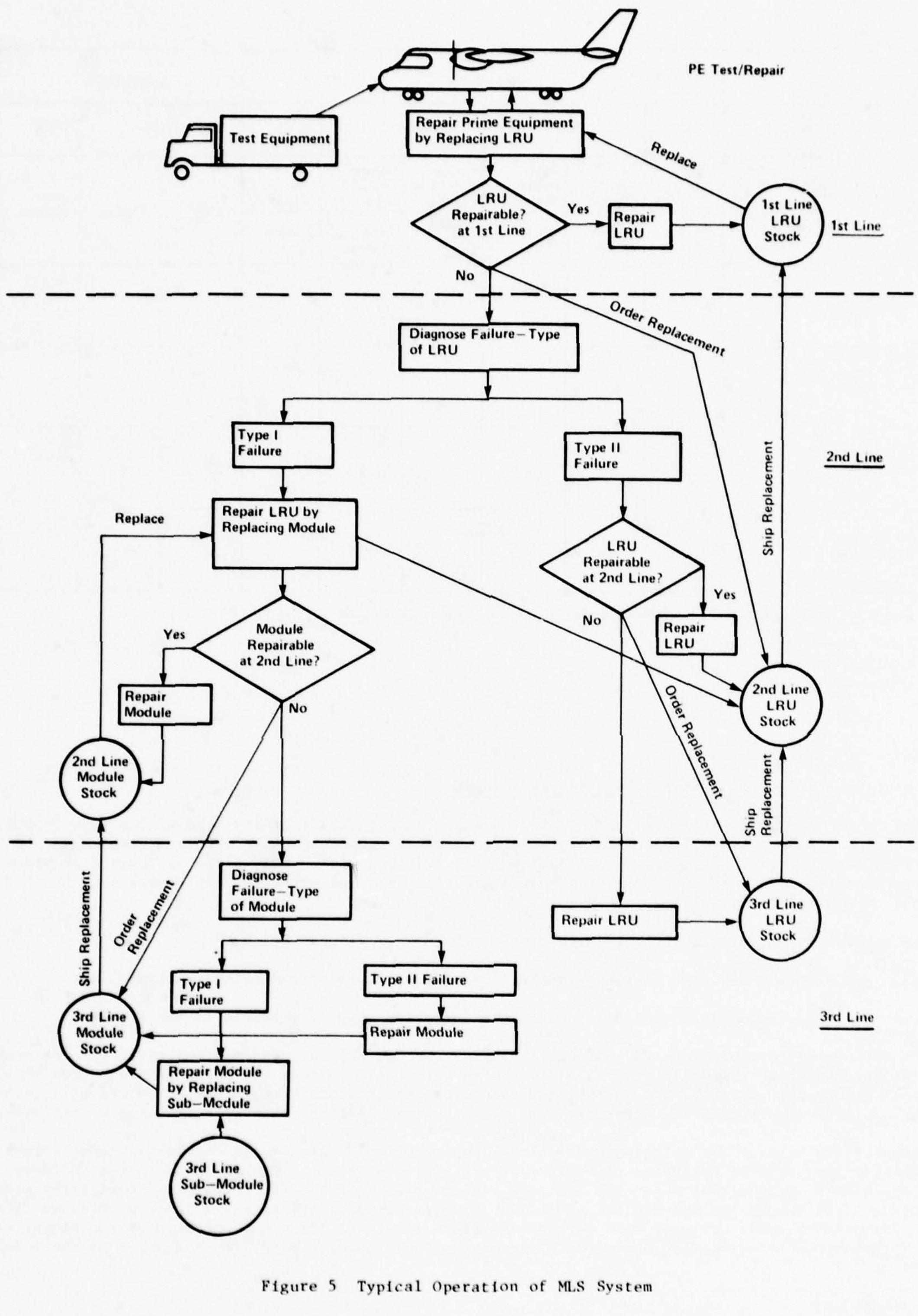

Figure 5 Typical Operation of MLS System

(b) Every prime equipment failure is caused by failure of a line replaceable unit

The DND LCC model operates on the understanding that a spare LRU will be required to restore operation of the prime equipment. This assumption neglects the possibility that some fraction of prime equipment failures may be repairable without the installation of a spare LRU, e.g. repaired by adjustment, etc. This assumption applies only to prime equipment failures. In the case of LRU failures and module failures, the model considers two types of restoration: by repair (Type II), and by replacement with a spare component (Type I). The impact of this assumption, depending upon the fraction of failures of this type, is that the DND LCC model will over-estimate the number of spare LRUs required, and will allow waiting time for obtaining the unneeded spare; that is, the DND LCC model output will to some extent, be more pessimistic than real life situation.

Table 2 Cost and SE Relationship Matrix

	Cost Elements \ SE Elements	PE MTBF	Util. Rate	No. of PE	MTBSM	Test Time	TE Qty	TE Operat. Readin	TE NFR	Supply Delay Time	Replace Time	Admin Time	Sched Maint Time	No. of Loctn. of PE	MLS System	Life of PE for LCC	Inherent Maint of PE
Non-Recurring	R & D Cost	●															●
	Hardware Acquisition Cost	●		●	●								●	●		●	●
	Disposal															●	
	Manpower Training for Operation		●	●										●			
	Document and Software for Operation			●										●			
	Operating Facilities			●										●			
	Initial Fuel Power and Consumables		●	●										●			
	Manpower Training for Maint.	●	●	●		●	●			●	●		●	●	●		●
	Document and Software for Maint.					●				●	●				●		●
	Test Equip. Cost					●	●	●	●					●			
	Repair Facilities									●				●	●		
	Initial Spares Cost									●				●	●		
	Initial Spares Transport Cost									●				●	●		
	Document for Logistics Support									●				●	●		
	Admin. Cost											●					
Recurring	Finance Charge			●										●	●		
	Fuel, Power and Consumables for Operation		●	●										●			
	Operating Manpower Cost		●	●										●			
	Maint. of Operating Facilities		●	●										●			
	Consumables for Repair	●	●	●						●	●		●	●	●		
	Maint. Manpower Cost	●	●	●	●	●	●	●	●	●	●		●	●	●		●
	Maint. of Repair Facilities													●	●		
	Spares Replacement Cost	●	●	●						●				●	●		
	Spares Replacement Cost	●	●	●					●	●				●	●		
	Manpower Cost for Logistics Support									●				●	●		
	Admin.											●					

(c) <u>No lateral transfer of spares occurs between spares pools</u>

All spares pools are assumed to obtain their spares from the preceding level of spares pool in the logistics support hierarchy. In real life, a spares pool may on occasion, for expediency, request a spare from another spares pool of the same level as itself. The effect of this real life practice, if permitted, would be to decrease the waiting time for a spare needed to make a repair. Thus the DND LCC model output does not allow for this occasional and irregular shortcut and hence could be pessimistic to some degree; the real life experience should be the same or better.

(d) <u>System effectiveness is measured as operational readiness</u>

The DND LCC model is constructed to measure system effectiveness in terms of operational readiness. This model does not consider operational performance or mission reliability; if these parameters are important on a particular project, the life cycle materiel manager must take them into account in his decision-making process.

(e) The DND LCC model requires input data

The DND LCC model deals in quantitative data. To exercise this model, the life cycle materiel manager must be able to provide input data. This input data can be estimated statistically based on historic experience or comparisons with similar equipment; input data can be based upon actual information, or it could be based on the personal judgment of the life cycle materiel manager, or even pure guesses. The operation of the DND LCC model does not depend upon the quality of input data but merely upon the availability of data on which to base its computations. In this respect, the accuracy of the output produced by the model will depend upon the quality of data provided. The better the estimates or data, the more accurate will be the DND LCC model output. However, by conducting sensitivity analyses, the life cycle materiel manager can identify those data items that have a strong impact on the model output, and those data items that have a lesser or negligible impact on output. In this way, he can determine which data items warrant the greatest effort in obtaining accurate estimates, and which data items can be estimated with less accuracy or even ignored.

(f) The DND LCC model considers quantitative data

The model does not deal with intangibles but in values that can be expressed quantitatively. Any applicable intangibles must be weighed by the life cycle materiel manager in the decision-making process.

(g) The DND LCC model is intended for comparative studies

This model should be used only for comparative studies. One indirect advantage of using a model for comparative studies is that it can be useful even when accurate input data are not available; if inputs are estimated in a consistent manner, even though they may err in absolute terms, the model can compute relative advantages or disadvantages of various options.

4. APPLICATION

4.1 Application of DND LCC Model to Life Cycle Management System

The DND LCC model is intended as a tool for carrying out comparative engineering studies of options and tradeable requirements available at different times or stages in the life cycle of a system or equipment. To do this, the DND LCC model evaluates each alternative in terms of LCC and operational readiness. Figure 6 illustrates typical applications for the DND LCC model throughout the various stages in the life cycle of a system or equipment. As the life cycle progresses, the alternatives available decrease. The model helps to compute quantitative data useful in assessing trade-offs between cost and effectiveness factors. It presents a powerful decision tool for the life cycle materiel managers.

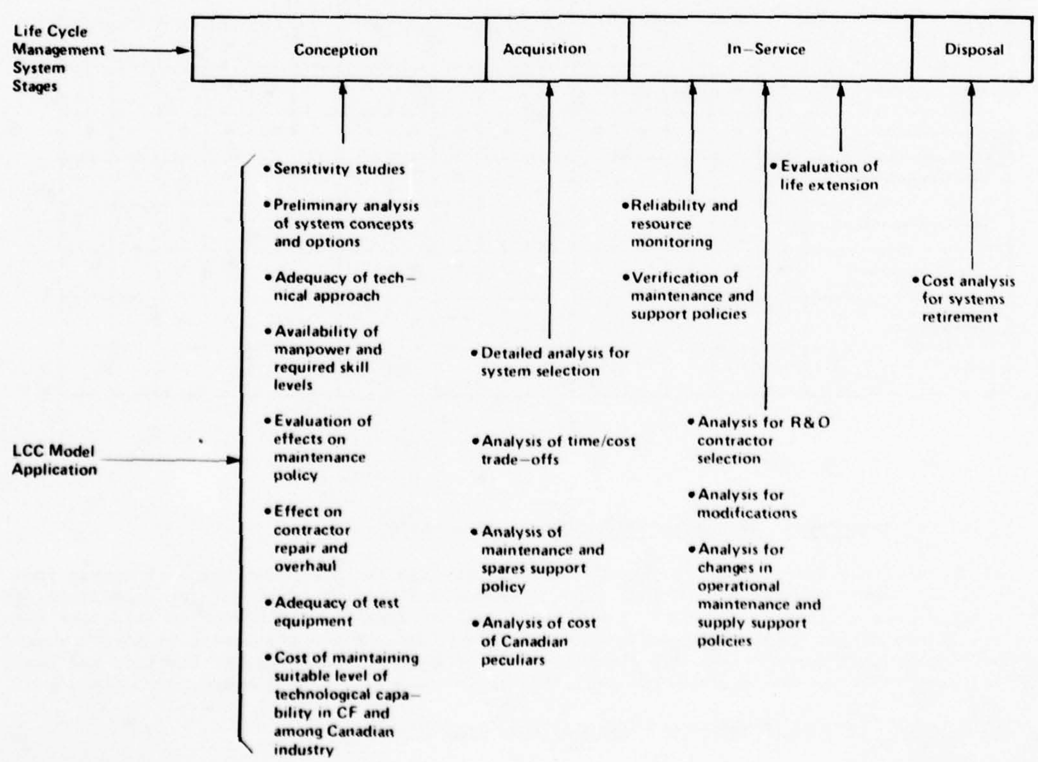

Figure 6 Application of LCC Model to Life Cycle Management System

4.2 A Decision Tool for Life Cycle Materiel Managers

The DND LCC model is highly adaptable. Its ultimate worth to the life cycle materiel manager will be determined by his vision in applying it, i.e. by the types of analyses and trade-off studies he decides to perform and his timing in conducting these studies. The model cannot make decisions but it can help answer questions. It is up to the life cycle materiel manager, however, to ask the right questions: what will be the effect on cost (or effectiveness)

... if expected system life is doubled? or halved?

... if the pipeline distance between 2nd and 3rd line is increased?

... if the system MTBF is improved?

... if more sophisticated test equipment are provided?

The tree diagram in Figure 7 illustrates how the DND LCC model can be used by the life cycle materiel manager in the decision-making process. The tree starts with a system effectiveness requirement; the first level of branching represents the choice between possible prime equipments. For each possible prime equipment, a second level of branching depicts the test equipment that might be used to support the prime equipment. The third level of branching represents possible repair policies, i.e. the particular MLS system chosen, including the many variables in this system, e.g. number of lines in the system, number of facilities at each line, distance between the lines, etc.

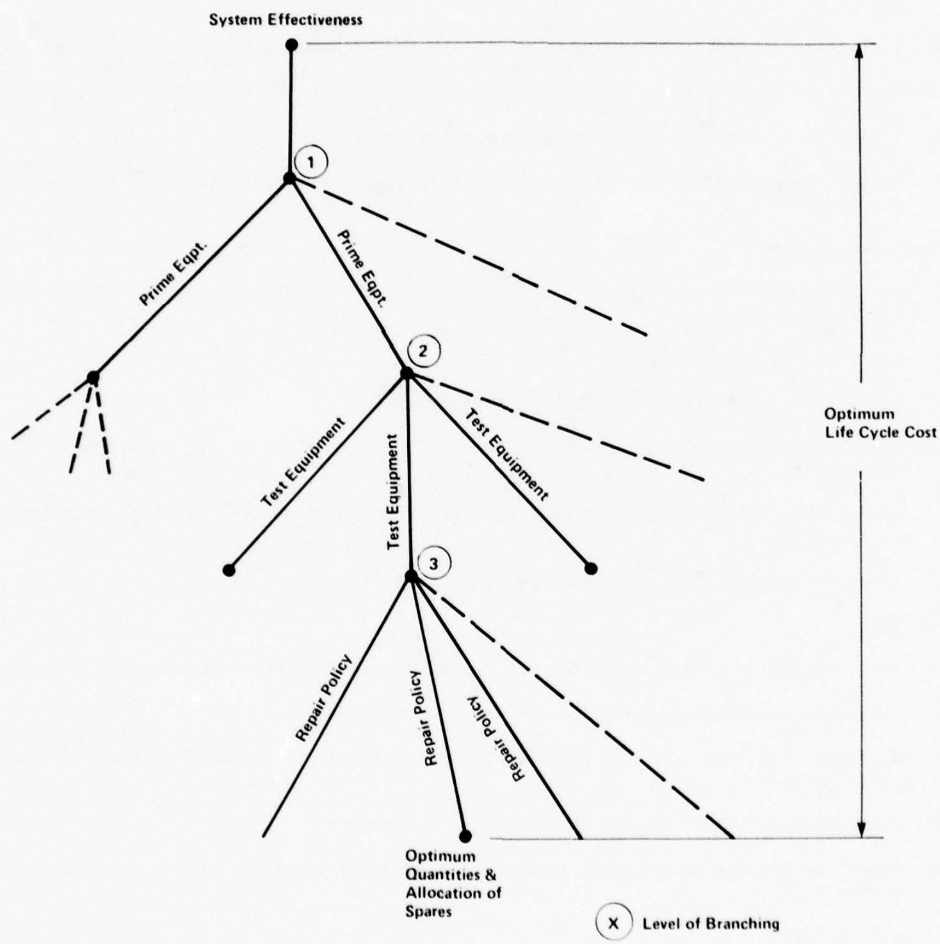

Figure 7 LCC Decision Tree

The final destination of each path, depending upon the choice made at each branching point, is the optimum number and allocation of spares needed. This destination can be determined by the DND LCC model, based upon a requirement for minimizing LCC or a requirement for maximizing system effectiveness.

At the conception stage, the possible decision paths include all branches. Once prime equipment has been selected, however, some branches are eliminated, but many choices still remain. Sometimes, the test equipment that may be selected depends on the choice of prime equipment, i.e. the prime equipment manufacturer may recommend a test equipment that is mandatory or at least desirable for use with the prime equipment.

The branches relating to the repair policy and MLS system to a large extent remain available throughout the life of the equipment. The DND LCC model can be used in the early stages of system life (conception, acquisition, beginning of in-service life) to evaluate possible MLS systems. This evaluation can usefully be repeated at intervals throughout the in-service life: to verify the MLS system selected earlier based on updated input data; to determine the impact of proposed equipment modifications; to determine the impact of a proposed change in effectiveness requirements, etc.

As the equipment nears the end of its useful life, the DND LCC model can evaluate options concerning possible modifications or overhaul to the prime equipment to extend its useful life versus the option of retiring the equipment and replacing it with new equipment.

4.3 Typical Applications

The following list names some of the applications of the DND LCC model that are typical for each stage of the LCMS:

(a) During conception

i) sensitivity studies to determine what parameters have a major impact on cost or system effectiveness

ii) analysis of options relating to system configuration, system reliability and maintainability, or operational readiness of the system with respect to LCC

iii) impact of possible combinations of manpower availability and skill level requirements on LCC

iv) evaluation of effect of maintenance policies on LCC and operational readiness

v) comparison of R&O contractor versus organic maintenance within DND in terms of LCC

vi) influence of test equipment on LCC and operational readiness

vii) evaluation of systems that are operationally equivalent (but different in other respects) in terms of LCC.

(b) During acquisition

i) evaluation for procurement of a system given a cost constraint or operational readiness requirement

ii) optimization of MLS system

iii) evaluation of maintenance policy in terms of LCC

iv) optimization of spares requirement given an operational readiness requirement or cost constraint

v) optimization of support resources, such as location of spares, level of maintenance, transportation

vi) forecasting of support expenditures over the life cycle.

(c) In-service

i) verification of analyses carried out during the conception or acquisition stage

ii) evaluation of proposed repair and overhaul contracts

iii) evaluation of impact on LCC and operational readiness of proposed software or hardware modifications

iv) evaluation of effect on LCC of changes in MLS system

v) impact on LCC and operational readiness of proposed modifications or overhaul to extend system life.

(d) At disposal stage

i) impact on LCC of extending system life versus replacing system with new acquisition

ii) evaluation of impact on LCC of available options in disposal, transportation, documentation, and administration to phase out system.

It should be noted that the exercise of the DND LCC model does not produce decisions; it only helps the life cycle materiel manager make more knowledgeable decisions.

4.4 The Decision-Making Process

In applying the LCC methodology, the decision process involves the following procedural steps:

(a) Definition of the problem

(b) Selection of alternatives that meet performance requirements

(c) Definition of input data requirements

(d) Acquisition of data

(e) Execution of model

(f) Interpretation of output

(g) Sensitivity analysis for cost drivers

(h) Evaluation of results with other intangible and uncontrollable parameters

(i) Final decision.

Figure 8 shows a simplified flow diagram for the decision-making process.

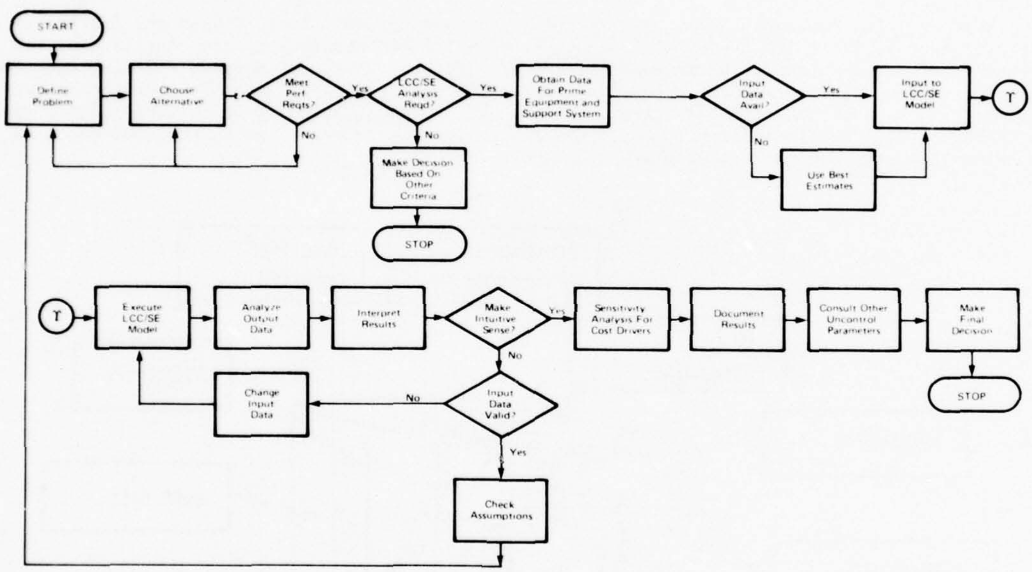

Figure 8 Decision-Making Flow Diagram

5. A CASE STUDY ON THE AN/ARN 504 MICROTACAN

5.1 Purpose of the Case Study

The purpose of the case study is to demonstrate the practical application of the DND LCC model, and to validate the LCC methodology developed for DND operation. The case study consists of a baseline study and three comparative studies to fully illustrate the features and capability of the DND LCC model as applied to the various stages of the system life cycle.

The system selected by DND as a vehicle to demonstrate the application of the DND LCC model is the Micro-Electronic Airborne TACAN, AN/ARN 504. It must be emphasized that the use of this system's data and configuration, including the support system, is for demonstration purposes only. Results presented herein make no implications concerning past decisions, or future actions, due to the fact that the baseline data provided by DND has been expanded to fully demonstrate the model's capability.

5.2 Scope of the Case Study

(a) Baseline study

This study deals with several hundred microtacan equipments deployed at a number of Canadian Forces bases. The prime equipments are supported by a three-echelon maintenance and logistics support system. There are 16 first lines supported by 4 second lines and 1 third line depot. Data on prime equipments and the support system were input to the model and used as a baseline in the three comparative studies.

(b) Study 1 - comparison of prime equipments for source selection

This study, conducted during the conception or acquisition stage, compares three different microtacan equipments for source selection. The trade-offs are between cost and reliability.

(c) Study 2 - comparison of alternate maintenance and logistics support plans

This study, usually conducted during early in-service stage, deals with the comparison of alternate maintenance and logistics support for the microtacan equipment.

(d) Study 3 - comparison of options for replacement of aging equipment

This study is usually conducted as the equipment approaches its disposal stage. It examines the options relating to replacement/modernization of aging equipment. This study is done to evaluate the economic viability of extending equipment service life.

Each of these studies was performed using the computerized DND LCC model. Details of the system operational scenario, data requirements, options considered, analysis results and conclusions are presented in the following sections. Complete case study on the AN/ARN 504 microtacan is documented in a BNR report on LCC Case Studies [4].

5.3 Baseline Study

This section describes aspects of the case study which are common and form a baseline for assessing alternatives.

(a) The system under study

Figure 9 illustrates the three LRUs of the microtacan system. Cost, weight and failure rate data are given in Table 3. The Receiver-Transmitter (R/T) LRU consists of its chassis plus ten replaceable modules (excluding the bandpass filter and isolator which are passive devices, non-repairable, and rarely require replacement). The Adapter LRU consists of its chassis plus two replaceable modules. The Control LRU is not further divisible into modules, and must be returned to the repair and overhaul (R&O) contractor for repair. The Mount, while referred to as an LRU, has not been included in this study due to its passive nature.

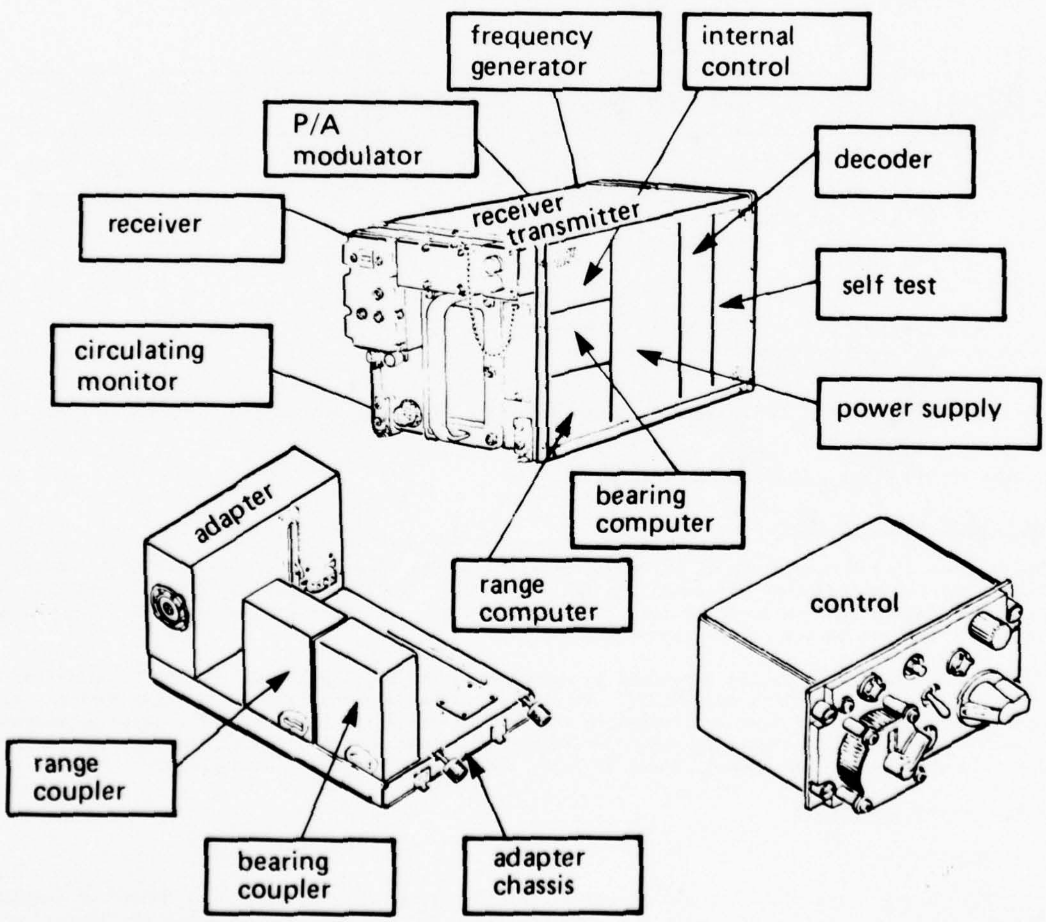

Figure 9 Micro-Electronic Airborne TACAN, AN/ARN 504

Table 3 Cost, Weight, and Failure Rate Data of the AN/ARN 504 Microtacan

LINE REPLACEABLE UNIT (LRU)	MODULE	COST ($)	WEIGHT (kg)	FAILURE RATE (x 10^{-6})
RECEIVER TRANSMITTER		21,000	10.7	5000
	P/A Modulator	2,750		405
	Frequency Generator	3,350		458
	Decoder	2,350		417
	Internal Control	1,650		769
	Bearing Computer	2,450		909
	Range Computer	2,100		540
	Circulating Monitor	750		48
	Self Test	950		196
	R/T Chassis	2,000		50
	Power Supply	1,550		804
	Receiver	2,870		148
ADAPTER		5,000	6.6	800
	Range Coupler	2,700		200
	Bearing Coupler	3,000		200
	Adapter Chassis	1,000		400
CONTROL		1,200	0.9	83

(b) Operation and support configuration

Figure 10 illustrates the operation and support configuration for the sixteen Canadian Forces bases where the microtacan equipments are located.

These sixteen 1st Line facilities are supported by four 2nd Line facilities which in turn are supported by a single 3rd Line maintenance depot. With the exception of the P/A modulator module in the R/T LRU, all other modules are serviced by the R&O contractor at the 3rd line depot.

The statistics concerning number of prime equipments (aircraft in this case), operating hours per month, and distances from supporting facilities, remain constant throughout the case study.

(c) Spares flow and repair activity

There are basic differences in the spares flow and repair activity between each of the microtacan LRUs. The baseline statistics used throughout these studies concerning order and shipping time, repair time, and percentage of occurrences, are given on each of the diagrams illustrating the respective activity for each of the LRUs. Figure 11 depicts baseline activity for the Control LRU, while Figures 12 and 13 cover the Adapter and R/T LRUs respectively.

In Figure 11, it can be seen that the Control LRU is sent to 2nd Line for failure verification and confirmation, and then either returned to stores if good, or sent to R&O for repair. Replacement Controls are ordered as indicated to replenish the respective spares stock.

Figure 12 concerns the Adapter LRU, whose activity parallels that of the Control LRU until confirmation of a fault at 2nd Line. Here, as there are modules involved, repair can be effected by module replacement.

With the R/T LRU, faults are liable to occur a small percentage of the time (5% in this case) which cannot be repaired by module replacement. This type of fault is defined as "Type II", whereas "Type I" faults refer to faults which module replacement can rectify. This is illustrated in Figure 13 where the spares flow and repair activity for the R/T is depicted.

(d) Input data

Table 4 lists the input data used in this case study.

The data used were the best available from DND at the time the study was performed. It was felt that using the best available data would make the case study more realistic, although it should be emphasized that the purpose of the case study was to exercise the DND LCC model rather than to draw conclusions concerning the microtacan system.

(e) Output

Figure 14 shows a plot of LCC vs OR for the baseline data inputs. This plot was obtained by varying the requirement for OR values between 0.7 and 0.998, and obtaining the resulting optimum values of LCC.

Table 4 Case Study Baseline Data

MODEL BLOCK REFERENCE	INPUT DESCRIPTION	INPUT DATA	UNITS
101	Period of Study in LCC Analysis	20	Years
102	Discount Rate	10	%/Annum
106	Non-Recurring Hardware: Acquisition Costs	27,300	Dollars
112	Non-Recurring Operating Costs: Documentation and Software	50	Dollars
122	Non-Recurring Maintenance Costs: Documentation and Software	900	Dollars
123	Transportation Cost Rate of Test Equipment	1	$/Ton-km
124	Non-Recurring Maintenance Costs: Repair Facilities	40,000	Dollars
132	Transportation Cost Rate for Spares	1	$/Ton-km
171	Annual Maintenance Cost: Consumables for Repair	1,400	$/Year
172	Loaded Labour Rate for Repair at PE Test/Repair Facility	14	$/Hour
172	Loaded Labour Rate for Repair at 1st Line MLS Facility	14	$/Hour
172	Loaded Labour Rate for Repair at 2nd Line MLS Facility	14	$/Hour
172	Loaded Labour Rate for Repair at 3rd Line MLS Facility	14	$/Hour
212	Average Operational Time of PE/Month	40	Hours/Month
212	Average Time PE Required to be Operable/Month	720	Hours/Month
231	Mean Test Time at PE Test/Repair Facility	2	Hours
233	No Fault Found Ratio	1/3	Fraction
240	Average LRU Replacement Time at PE Test/Repair Facility	1	Hours
266	Number of LRUs in PE	3	Number
277	Average Actual Repair Time at 2nd Line	6	Hours
281	Average Actual Repair Time at 3rd Line	20	Hours

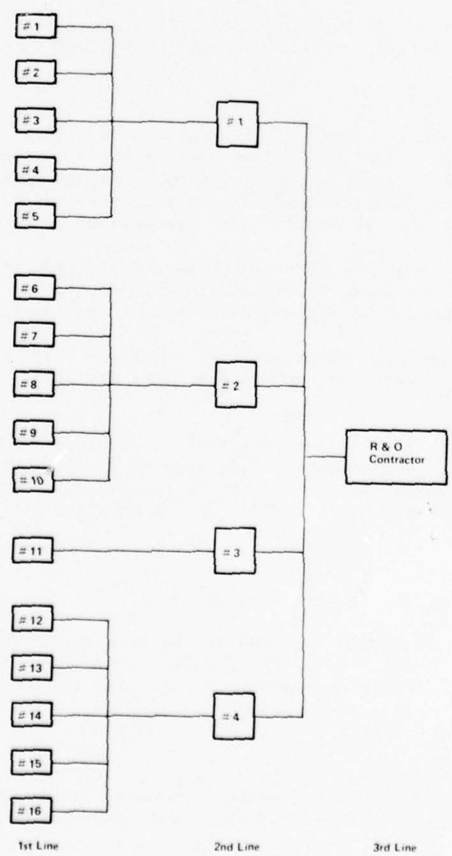

Figure 10 Operation and Support Configuration

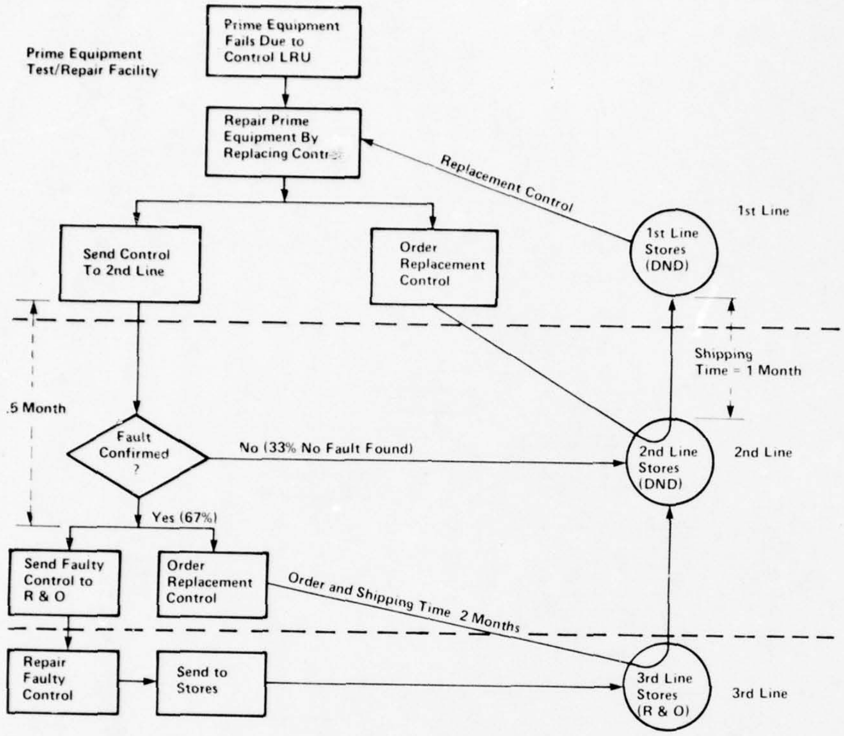

Figure 11 Baseline Repair Activity for Control LRU

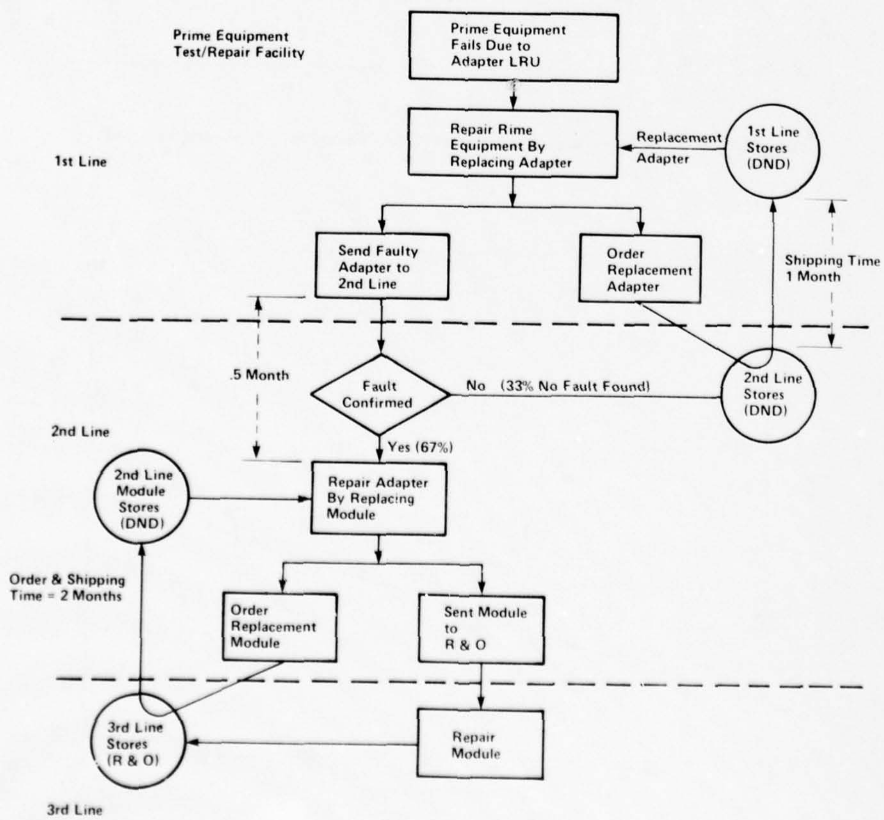

Figure 12 Baseline Repair Activity for Adapter LRU

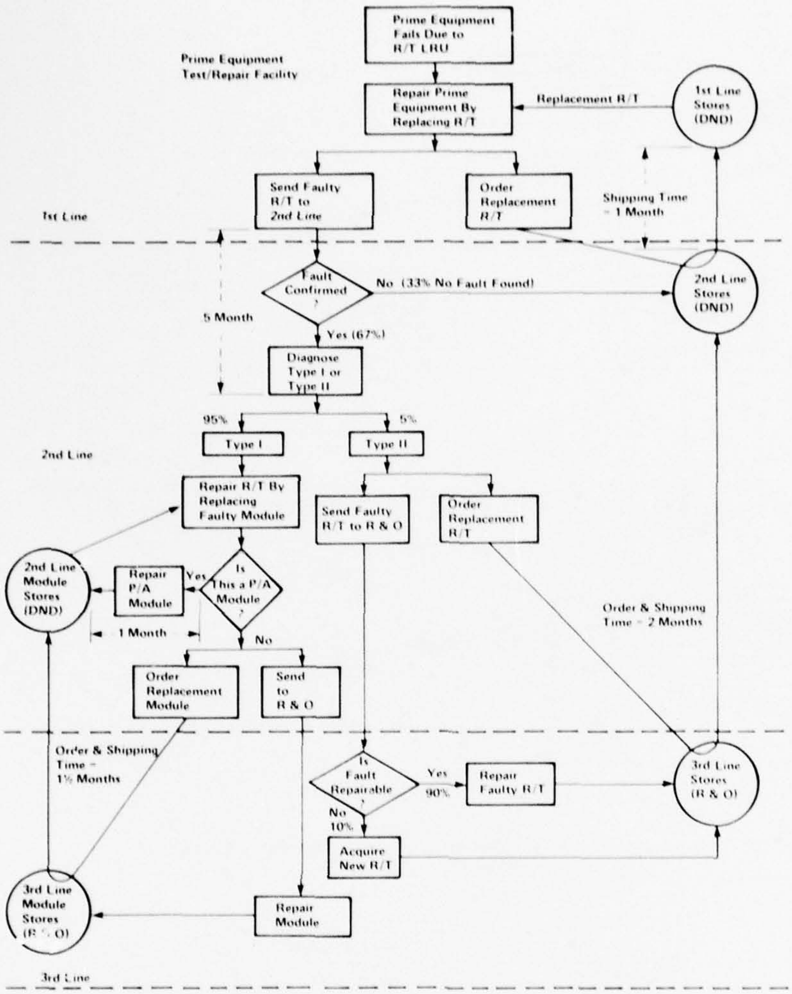

Figure 13 Baseline Repair Activity for Receiver/Transmitter LRU

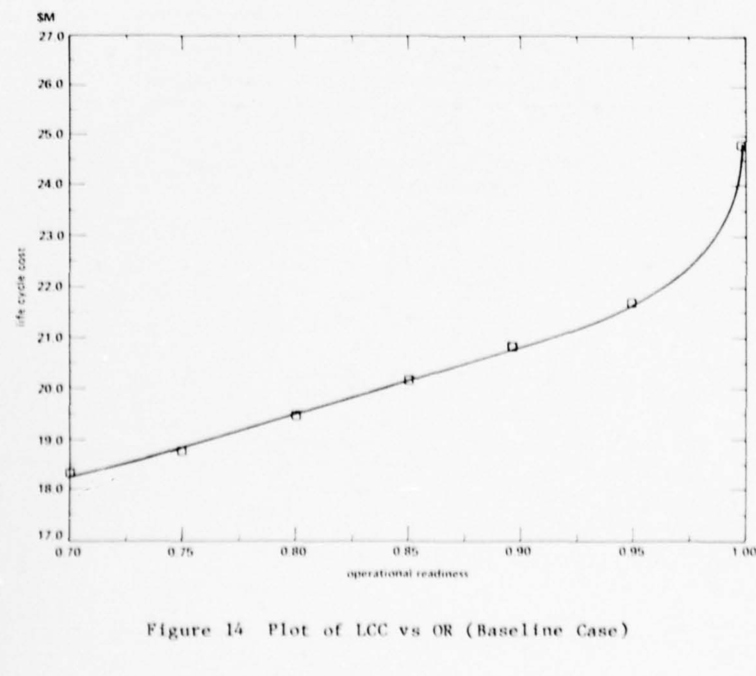

Figure 14 Plot of LCC vs OR (Baseline Case)

A summary printout is shown in Figures 15 and 16 for one of the points on the graph (OR = 0.80, LCC = $19,455,024).

OPERATIONAL READINESS SUMMARY

PE LOCATION	MEAN UPTIME (210) HOURS			MEAN DOWNTIME (220) HOURS							OPERATIONAL READINESS
				CORRECTIVE (221)					SCHEDULED		
	MTBF (211)	MTBSM (214)	(210)	TE TIME (230)	SPARES (260)	REPLACE (240)	ADMIN (250)	(221)	(222)	(220)	EACH PE
# 1	3059.67	0.0	3059.67	2.60	684.06	1.30	0.0	687.96	0.0	687.96	0.8164
# 2	3059.67	0.0	3059.67	2.60	744.41	1.30	0.0	748.31	0.0	748.31	0.8035
# 3	3059.67	0.0	3059.67	2.60	700.89	1.30	0.0	704.79	0.0	704.79	0.8128
# 4	3059.67	0.0	3059.67	2.60	897.60	1.30	0.0	901.50	0.0	901.50	0.7724
# 5	3059.67	0.0	3059.67	2.60	1402.99	1.30	0.0	1406.89	0.0	1406.89	0.6850
# 6	3059.67	0.0	3059.67	2.60	755.47	1.30	0.0	759.37	0.0	759.37	0.8054
# 7	3059.67	0.0	3059.67	2.60	752.59	1.30	0.0	756.49	0.0	756.49	0.8016
# 8	3059.67	0.0	3059.67	2.60	1082.80	1.30	0.0	1086.70	0.0	1086.70	0.7379
# 9	3059.67	0.0	3059.67	2.60	764.71	1.30	0.0	768.61	0.0	768.61	0.7992
#10	3059.67	0.0	3059.67	2.60	1082.80	1.30	0.0	1086.70	0.0	1086.70	0.7379
#11	3059.67	0.0	3059.67	2.60	747.42	1.30	0.0	751.32	0.0	751.32	0.8029
#12	3059.67	0.0	3059.67	2.60	754.48	1.30	0.0	758.37	0.0	758.37	0.8056
#13	3059.67	0.0	3059.67	2.60	848.33	1.30	0.0	852.23	0.0	852.23	0.7821
#14	3059.67	0.0	3059.67	2.60	719.76	1.30	0.0	723.66	0.0	723.66	0.8087
#15	3059.67	0.0	3059.67	2.60	821.23	1.30	0.0	825.13	0.0	825.13	0.7876
#16	3059.67	0.0	3059.67	2.60	677.37	1.30	0.0	681.27	0.0	681.27	0.8179

OVERALL PRIME EQUIPMENT OPERATIONAL READINESS IN THE SYSTEM = 0.800983

LEGEND

ITEM	MODEL BLOCK REF. NUMBER	DESCRIPTION
MTBF	211	*Mean* Calendar Time Between Failures
MTBSM	214	Mean Calendar Time Between Scheduled Maintenance (Note: 0.0 represents no Scheduled Maintenance
MEAN UPTIME	210	A Function of MTBF and MTBSM
TE TIME	230	Mean Test Time for Corrective Maintenance
SPARES	260	Mean Supply Delay Time for Corrective Maintenance
REPLACE	240	Mean LRU Replacement Time for Corrective Maintenance
ADMIN	250	Mean Administration Time for Corrective Maintenance
CORRECTIVE	221	Sum of above Four Downtimes
SCHEDULE	222	Mean Downtime to perform Schedule Maintenance
MEAN DOWNTIME	220	A Function of Corrective and Scheduled Maintenance Downtimes
OPERATIONAL READINESS		OR of each PE at each given location (Computed from Mean Uptime and Mean Downtime)

Figure 15 Operational Readiness Summary (Baseline Case)

```
                         LIFE CYCLE COST SUMMARY

            LCC:                                       $ 19.455024 M

NON-RECURRING(104):                             $14.520843 M
(PRESENT VALUE)

    RES & DEV(105):                        $ 0.0
    HARD. ACQ.(106):                       $11.547900
    DISPOSAL(107):                         $ 0.0
    OPERATING(110):                        $ 0.021150
        MANPOWER(111):               $ 0.0
        DOCUMENT(112):               $ 0.021150
        OPERATING(113):              $ 0.0
        CONSUMABLES(114):            $ 0.0
    OTHER COSTS(115):                      $ 0.0
    MAINTENANCE(120):                      $ 0.858900
        MANPOWER(121):               $ 0.0
        DOCUMENT(122):               $ 0.018900
        TEST EQUIPMENT(123):         $ 0.0
        REP FACILITIES(124):         $ 0.840000
    LOGISTICS(130):                        $ 2.092895
        INITIAL SPARES(131):         $ 2.091190
        TRANSPORT(132):              $ 0.001705
        DOCUMENT(133):               $ 0.0
    ADMINISTRATION(140):                   $ 0.0

RECURRING(150):                                 $ 0.579583 M/YEAR

    OPERATING(160):                        $ 0.0
        CONSUMABLES(161):            $ 0.0
        MANPOWER(162):               $ 0.0
        MAINTENANCE(163):            $ 0.0
    MAINTENANCE(170):                      $ 0.462576
        CONSUMABLES(171):            $ 0.029400
        MANPOWER(172):               $ 0.433176
            SCHED. REPAIR:  $ 0.0
            PE REPAIR:      $ 0.021740
            1ST REPAIR:     $ 0.0
            2ND REPAIR:     $ 0.101462
            3RD REPAIR:     $ 0.309975
        MAINTENANCE(173):            $ 0.0
    LOGISTICS(180):                        $ 0.117007
        SPARES REPLACE(181):         $ 0.109154
        TRANSPORT(182):              $ 0.007853
        MANPOWER(183):               $ 0.0
    ADMINISTRATION(190):                   $ 0.0
-------------------------------------------------------------------------

OVERALL PRIME EQUIPMENT OPERATIONAL
READINESS IN THE SYSTEM =  0.800983
```

LEGEND:

ITEM	MODEL BLOCK REF. NUMBER	DESCRIPTION
LCC	100	Total Life Cycle Cost over System Life
NON-RECURRING COSTS	104	Costs incurred only one during System Life
RES. & DEV.	105	Research and Development Costs
HARD. ACQ.	106	Hardware Acquisition Costs
DISPOSAL	107	Gain, or Loss from Phasing out Equipment or Systems
OPERATING	110	One-Time Operating Costs
MANPOWER	111	One-Time Operating Training Costs, including Manpower and Training Aids
DOCUMENT	112	One-Time Costs for Operating Manuals, Technical Orders Software, etc.
OPERATING	113	One-Time Cost of Facilities to house and operate a System
CONSUMABLES	114	Initial Fuel Power and Consumables
OTHER COSTS	115	Other One-Time Costs not categorized above
MAINTENANCE	120	One-Time Costs associated with Maintenance
MANPOWER	121	One-Time Maintenance Training Costs, including Aids
DOCUMENT	122	One-Time Costs for Maintenance Documentation
TEST EQUIPMENT	123	One-Time Test Equipment Costs for Maintenance
REP. FACILITIES	124	One-Time Costs of Establishing Repair Facilities
LOGISTICS	130	One-Time Logistics Support Costs
INITIAL SPARES	131	One-Time Cost for Initial Spares
TRANSPORT	132	Transportation Cost for Logistic Support
DOCUMENT	133	One-Time Costs associated with Logistics Support
ADMINISTRATION	140	One-Time Administrative Costs for Project Management
RECURRING	150	Repetitive Ongoing Costs
OPERATING	160	Recurring Costs for System Operation
CONSUMABLES	161	Fuel Power and Consumables for System Operation
MANPOWER	162	Recurring System Operating Costs incl. Training
MAINTENANCE	163	Recurring Cost for Maintenance of Operating Facilities
MAINTENANCE	170	Recurring Costs for Repair and Maintenance
CONSUMABLES	171	Recurring Cost of Consumables for Repair
MANPOWER	172	Recurring Maintenance Manpower Costs
SCHED. REPAIR	172	Recurring Costs for Scheduled Maintenance
PE REPAIR	172	Maintenance Labour Costs at Prime Equipment Location
1st REPAIR	172	Maintenance Labour Costs at 1st Line
2nd REPAIR	172	Maintenance Labour Costs at 2nd Line
3rd REPAIR	172	Maintenance Labour Costs at 3rd Line
MAINTENANCE	173	Recurring Costs for Maintenance of Repair Facilities
LOGISTICS	180	Recurring Costs for Logistics Support
SPARES REPLACE	181	Cost to Replenish Spares Inventory
TRANSPORT	182	Recurring Cost of Transporting Spares
MANPOWER	183	Recurring Manpower Costs for Logistics Support
ADMINISTRATION	190	Recurring Administration Costs

Figure 16 Life Cycle Cost Summary (Baseline Case)

5.4 Study 1 - Comparison of Prime Equipments for Source Selection

(a) Description

Study 1 deals with the selection of three alternative microtacan systems on a LCC basis. The repair and maintenance policy is equivalent for all three alternatives.

This study could take place in either the conception or acquisition stage of the LCMS. The basic approach is the same in either stage, only the depth of analyses would differ depending upon the data availability and accuracy.

The alternative microtacan systems will be referred to as Alternates A, B and C, with Alternate A being the baseline system as described in the previous section.

The following data changes apply to Alternate B and Alternate C.

Alternate B. Costs for LRUs and modules are 120% of the baseline figures shown in Table 3. Failure rates are 50% of the baseline figures shown in Table 3.

Alternate C. Costs for LRUs and modules are 150% of the baseline figures shown in Table 3. Failure rates are 50% of the baseline figures shown in Table 3.

The baseline support system is applied in all three alternatives.

(b) Results

The results obtained from exercising the DND LCC model with the input data described for Alternates A, B and C are shown graphically in Figure 17. The data computed by the model for an OR of 0.80 were analyzed and the results summarized in Table 5.

Table 5 Life Cycle Cost Breakdown (Study 1)

ALTERNATIVE	NON-RECURRING (NR)	RECURRING (LCC-NR)	TOTAL LCC
A (baseline)	\$ 14.52M	\$ 4.93M	\$ 19.45M
B	\$ 15.16M	\$ 2.37M	\$ 17.53M
C	\$ 19.10M	\$ 2.43M	\$ 21.53M

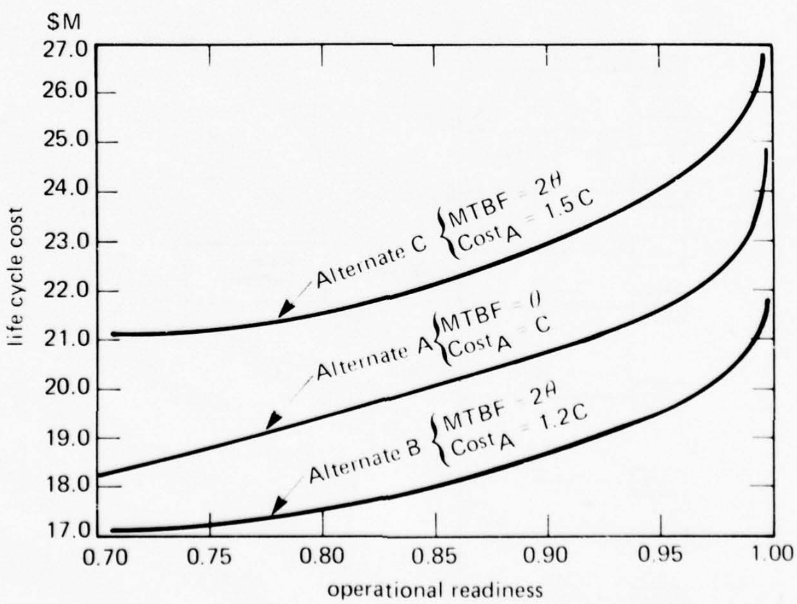

Figure 17 Plot of LCC vs OR (Study 1)

(c) Conclusions

It can be concluded from this particular study that a limit exists to the costs which should be incurred for hardware acquisition, in order to achieve lower hardware failure rates, for any specified value of equipment operational readiness.

From the LCC breakdown in Table 5 and related analyses, the following conclusions can also be drawn:

i) The recurring costs are virtually halved by halving the failure rates.

ii) While the initial spares are less for reduced failure rates, the cost is offset to a varying extent by an increase in hardware acquisition cost.

It should be noted that only by plotting a family of curves can a proper appreciation be obtained of these effects.

5.5 Study 2 - Comparison of Alternate Maintenance and Logistics Support Plans

(a) Description

Study 2 demonstrates the use of the DND LCC model in making comparisons between alternative maintenance and logistics support systems. The microtacan equipment details are as described in the baseline case.

The alternative support systems are referred to as Alternate A and Alternate B.

Alternate A. The support system is as described for the baseline case.

Alternate B. The support system is depicted in Figure 18. Essentially all 2nd Line maintenance has been eliminated, and the proposition is made to ship all failed items (LRUs in this case) directly to 3rd Line (i.e. the R&O contractor). Figure 19 illustrates the repair activity which will take place under this alternative support system.

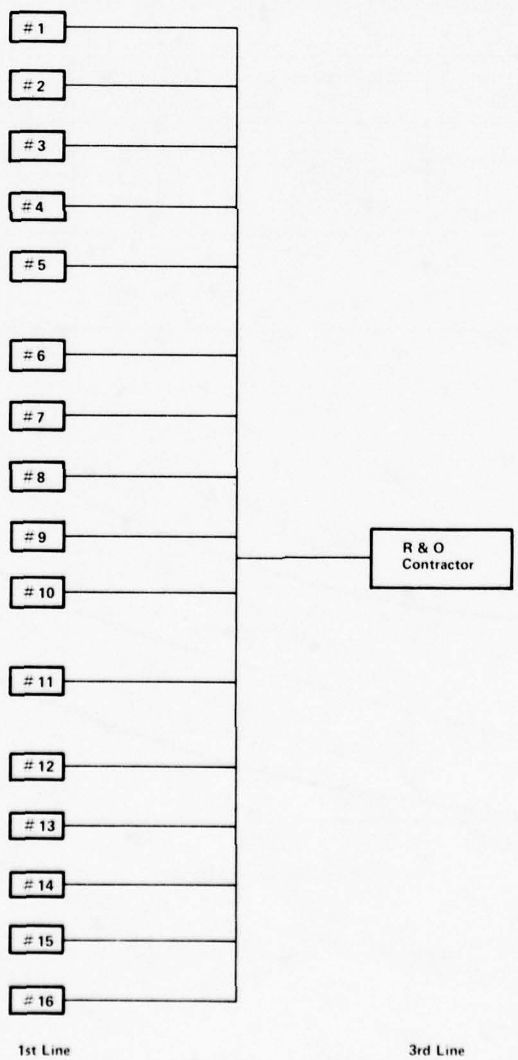

Figure 18 Operation and Support Configuration (Study 2)

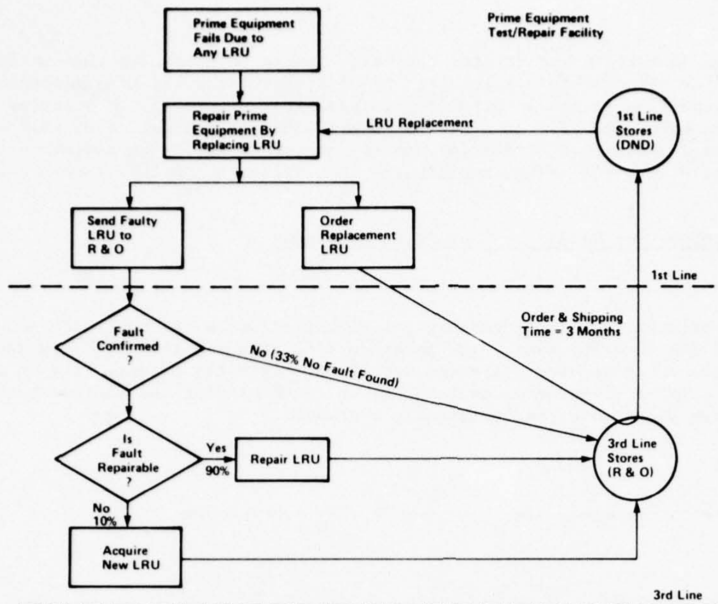

Figure 19 Repair Activity for Alternative B (Study 2)

(b) Results

The results obtained in this study from applying alternative support systems are graphically displayed in Figure 20.

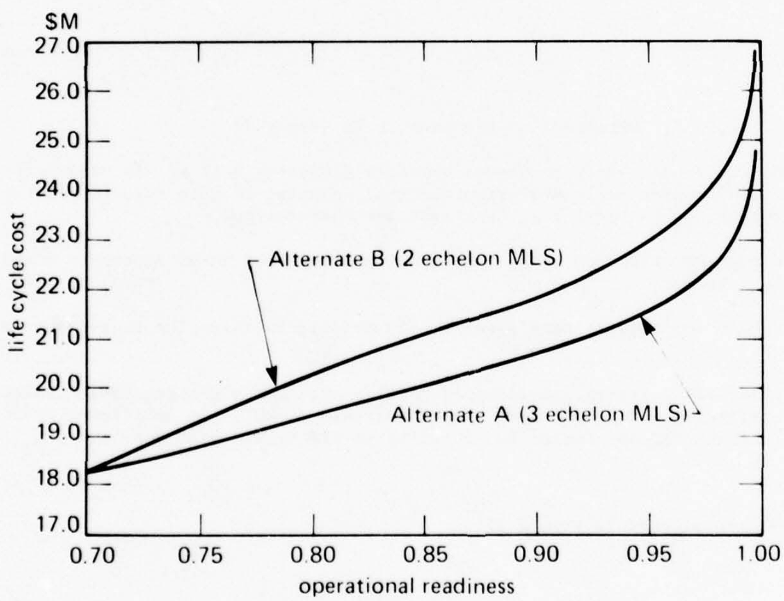

Figure 20 Plot of LCC vs OR (Study 2)

The data computed by the model for an OR of 0.80 were analyzed and the results summarized in Table 6.

Table 6 Life Cycle Cost Breakdown (Study 2)

ALTERNATIVE	NON-RECURRING (NR)	RECURRING (LCC-NR)	TOTAL LCC
A (baseline)	\$ 14.52M	\$ 4.93M	\$ 19.45M
B	\$ 16.68M	\$ 3.65M	\$ 20.33M

(c) Conclusions

From the LCC breakdown in Table 6 and related analyses, it can be concluded that while the recurring costs of manpower for maintenance are reduced, by eliminating the 2nd Line maintenance activity, the extra (non-recurring) costs incurred for initial spares outweigh this factor and make the proposed support system more expensive on a LCC basis over the upper range of OR (0.7 and up). At lower values of OR the reduced amount of initial spares required reduces the advantage of one maintenance policy over the other. It is not anticipated that values of OR less than 70% would be of practical interest.

5.6 Study 3 - Comparison of Options for Replacement of Aging Equipment

(a) Description

Study 3 examines two alternatives in a hypothetical situation where the equipment and support system are as described in the baseline case. The point in time at which this study is assumed to take place is after 15 years of in-service operation out of an originally planned life of 20 years (see Figure 21). At this point consideration is being given to continuing the equipment use for another ten years (i.e. five years more than originally planned).

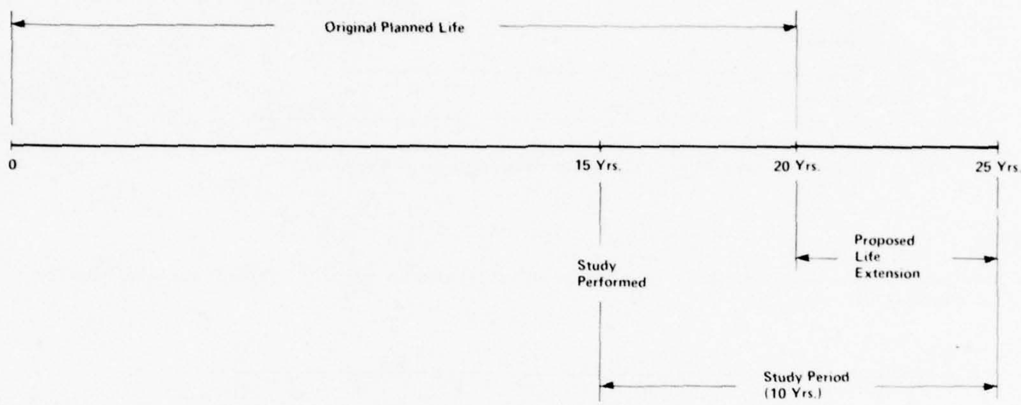

Figure 21 Extension of Equipment Life (Study 3)

It is assumed that the power supply module is now only achieving half of its originally specified MTBF. All other modules meet their MTBF requirements. Because of this reduced MTBF of the power supply, the microtacan operational readiness is lower than desired.

The two alternate courses of action being considered are referred to as Alternate A and Alternate B, and are described below:

Alternate A. Purchase additional spare power supply modules to raise the microtacan operational readiness.

Alternate B. Replace all existing power supply modules with a new design, having twice the MTBF specified for the existing model, but with a cost increase of 20%. An additional $100K onetime cost is also added to account for the design and retrofit of the replacement module.

(b) Results

Results of study 3 are plotted in Figure 22.

(c) Conclusions

It may be concluded from this study that Alternate A, although more costly in the mid-range of OR, is not significantly greater, and has the advantage of verified data to support it. Alternate B may be more costly in the long run if the failure rate again does not hold to the specified value.

6. CONCLUSIONS

The case study on the AN/ARN 504 microtacan has successfully demonstrated the application of the DND LCC model to the Canadian Forces operating environments. The success of this demonstration has led to the award of several further contracts to BNR, ranging from LCC evaluation of aircraft engine availability to comparison of replacement policies for a vehicle fleet.

The LCC methodology was developed primarily to meet the needs of DND. By standardizing on this methodology, DND obtains a common starting point for LCC evaluations. The methodology could be extended to non-DND applications to conduct LCC and system effectiveness analyses on complex systems such as power distribution, transportation, and communication networks. The methodology can also be adapted to specific requirements for sensitivity analyses, evaluation of reliability improvement warranties, engineering economy studies, and other applications.

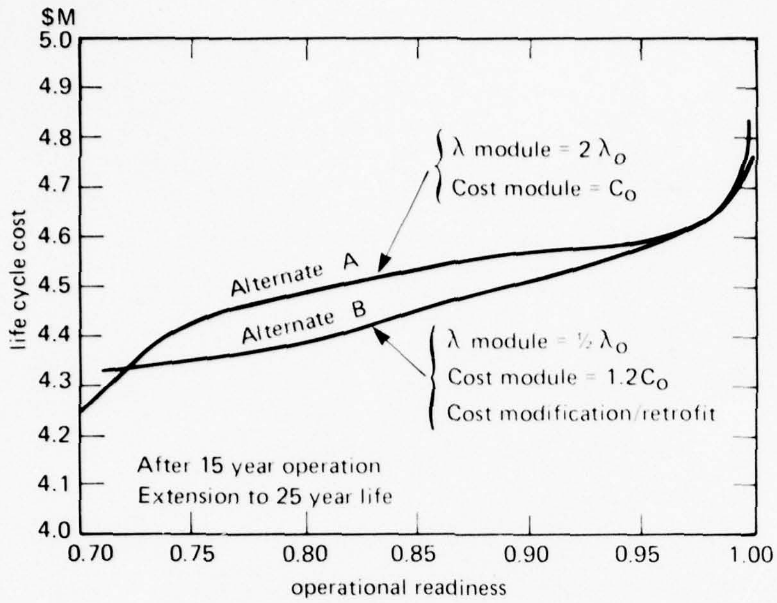

Figure 22 Plot of LCC vs OR (Study 3)

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2. Barasia, R.K., Mathematical Model - Development of a Life Cycle Management Cost Model, Report No. 5J30-4082-5, Bell-Northern Research, published under DSS contract No. OSR5-0102 for the Department of National Defence, Ottawa, Canada, December 1977.

3. Barasia, R.K., Brook, C.R. and Williams, R.B., Methodology - Development of a Life Cycle Management Cost Model, Report No. 5J30-4082-2, Bell-Northern Research, published under DSS contract No. OSR5-0102 for the Department of National Defence, Ottawa, Canada, April 1977.

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ACKNOWLEDGEMENTS

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RECENT EXPERIENCE IN THE DEVELOPMENT AND APPLICATION OF LCC MODELS

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SUMMARY

As operation and support costs of the complex, sophisticated weapon systems of today have begun to far exceed the original acquisition costs, there has been increasing pressure to develop and implement Life Cycle Cost (LCC) methodology in the analysis of such systems. To use such a methodology, one must have available valid models which incorporate acquisition costs and operation and support costs over some defined useful life period. Many models have been developed, but it has only been recently that they have begun to be applied. The purpose of this paper is to: (1) acquaint you with a few of the representative, available models; (2) discuss the methods by which the models were developed; (3) analyze the models in terms of their shortcomings and sensitivities, and (4) discuss recent applications of these models in avionics procurements. A brief bibliography, containing information on additional models, is included.*

INTRODUCTION: The Life Cycle costs of a system include its acquisition costs and its operating and maintenance (O&M) costs for its useful life. From this may be subtracted any salvage value recovered at the end of its useful life. The latter is usually negligible and will not be addressed in this paper. We will address, in order, acquisition cost models, O&M cost models, a model examining reliability as a capital investment, considerations of inaccuracy in LCC estimates and some recent applications of LCC models in Air Force procurements.

ACQUISITION COST MODELS: Acquisition cost models are usually characterized by two types: development cost models, and production cost models. Acquisition cost models are usually empirical in nature (although there are some exceptions). They are generally developed directly from available data; the inherent correlation and relationships among the data variables are allowed to frame the form of the resulting model. One obvious modeling approach is the use of multiple regression in which one develops a mathematical relationship between acquisition costs and the significant variables affecting acquisition costs. Regression analysis is a widely used modeling technique and hence, merits some discussion.

SIMPLE LINEAR REGRESSION: We shall illustrate the use of regression techniques by using simple linear regression to derive a model relating the cost of airborne radio sets to their weight. This is based on an intuitively appealing thesis that as the weight of a system increases it becomes more costly. It is unlikely that weight alone will prove a satisfactory indication of cost, but this will be checked in the course of the analysis. Our input data is presented in Table 1.

TABLE 1
TEN AIRBORNE RADIO COMMUNICATION SETS

COST ($)	WEIGHT (LB)
22,200	90
17,300	161
11,800	40
9,600	108
8,800	82
7,600	135
6,800	59
3,200	68
1,700	25
1,600	24

*The authors above are particularly indebted to the authors of the following reports and publications, extracts from which form a major portion of this lecture text.

(1) "An Introduction to Equipment Cost Estimating", C. A. Batchelder, et al, The Rand Corporation, RM-6103-SA, December 1969.
(2) "Reliability Acquisition Cost Study", S.D. Mercurio and C. W. Shaggs, RADC-TR-77-334, June 1973.
(3) "Reliability Acquisition Cost Study (II), Hughes Aircraft Company, RADC-TR-75-270, November 1975.
(4) "Reliability Trade-offs for Unit Production Cost", T.W. Butler, June 1978, in printing as an RADC Technical Report.
(5) "Reliability as a Capital Investment", A. Coppola, Proceedings 1974 Annual Reliability and Maintainability Symposium, Los Angeles, California, 29-31 January 1974.

The form of the relationships between cost and the explanatory variable(s) depends on the problem. It may reflect either an underlying physical law or a structural relationship. When no particular functional form is suspected, a simple (two-variable) linear model is frequently used to describe the relationship between two variables. In this case, the equation of the model is

$$y = a + bx, \tag{1}$$

where y is the dependent variable and x is the explanatory variable. The symbols a and b are the constant and coefficient, respectively, of the equation estimated from the data. Here y could represent the cost of a radio communication set and x could represent the weight. If it is assumed that b is greater than zero, the model indicates that heavier equipment will cost more than lighter equipment. When the values of a and b are known, it is possible to compute y (cost) for any given value of x (weight).

LEAST-SQUARES ESTIMATING: Given Eq. (1), the basic problem in the first phase of the regression analysis is to derive estimates of the parameters a and b. The standard procedure is the method of least-squares. The values of a and b are determined by the requirement that the sum of the squares of the deviations of the sample observations from the estimated line will be at a minimum. Symbolically, this minimum is expressed as

$$\min \sum_{i=1}^{n} (y_i - \hat{y}_i)^2, \tag{2}$$

Where y_i is the ith observation and $\hat{y}_i$ is the value of y_i estimated from the equation

$$\hat{y}_i = \hat{a} + \hat{b}x_i. \tag{3}$$

The carets over $\hat{a}$ and $\hat{b}$ indicate that $\hat{a}$ and $\hat{b}$ are least-squares estimates of the true but unknown values of a and b. Thus $\hat{y}_i$ is the least-squares estimate of y_i and the term $(y_i - \hat{y}_i)$ indicates the difference between each observed y_i and each corresponding estimated $\hat{y}_i$. This is illustrated in Fig. 1, which shows the actual (y) and estimated ($\hat{y}$) value of the dependent variable that corresponds

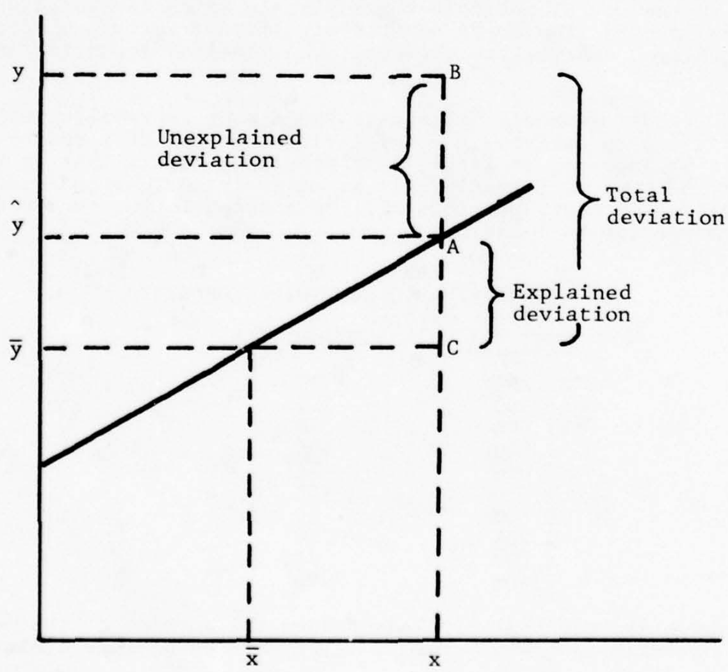


FIG. 1 - DEVIATION OF ACTUAL VALUE FROM ESTIMATED VALUE AND SAMPLE MEAN

to a specific value of the explanatory variable x. The line shown in Fig. 1 is the line that represents Eq. (3). All of the estimated values of $\hat{y}_i$ fall on this line. The vertical distance from point A to point B is the difference between the actual value (y) and the estimated value ($\hat{y}$). The summation of all such differences that are squared (as illustrated in Eq. (2)) is the quantity to be minimized in estimating the line.

The minimum value for this sum is satisfied by substituting Eq. (3) in Eq. (2), taking the partial derivatives of Eq. (2) with respect to $\hat{a}$ and $\hat{b}$, and setting the results equal to zero. This process yields two equations that are called normal equations and that can be solved for $\hat{a}$ and $\hat{b}$:

$$\Sigma\, y = n\hat{a} + \hat{b}\, \Sigma\, x,$$

$$\Sigma\, xy = \hat{a}\, \Sigma\, x + \hat{b}\, \Sigma\, x^2,$$

where y = cost of airborne radio equipment in thousands of dollars,
x = weight of airborne radio equipment in pounds,
n = number of items in the sample,
Σ = summation (e.g., $\Sigma\, y$ = the sum of all y's).

Table 2 contains the numerical values and totals required to solve the

TABLE 2
DATA FOR REGRESSION ANALYSIS OF COST AND WEIGHT

x	y	x^2	xy
90	22.2	8,100	1,998.0
161	17.3	25,921	2,785.3
40	11.8	1,600	472.0
108	9.6	11,664	1,036.8
82	8.8	6,724	721.6
135	7.6	18,225	1,026.0
59	6.8	3,481	401.2
68	3.2	4,624	217.6
25	1.7	625	42.5
24	1.6	576	38.4
792	90.6	81,540	8,739.4

normal equations when data from Table 1 are used. The costs are expressed in thousands of dollars. When the values from Table 2 are substituted in the normal equations, the following expressions are obtained for the sample data points (n = 10):

$$90.6 = 10a + 792b,$$

$$8739.4 = 792a + 81,540b.$$

Solved simultaneously, these equations give

$$\hat{a} = 2.477,$$

$$\hat{b} = .083,$$

and thus from Eq. (3)

$$\hat{y} = 2.477 + .083x \tag{4}$$

The line represented by this equation is shown in Fig. 2 as the solid line with the actual observations plotted as dots. The extent of the dispersion of the observations relates inversely to the usefulness of the line as a tool for estimating the values of y from the values of x. The greater the dispersion of observed values of y about the line, the less accurate the estimates that are based on the line are likely to be. The measure of the dispersion about the regression line is called the standard error of estimate (SE) of the equation and is shown by the dashed lines.

One measure of dispersion in a collection of data points is called the variance. The variance is defined as the sum of the squared distances to each of the data points from a central reference point divided by the degrees of freedom (df), which equal the number of independent bits of information contained in the sample. (In analyzing the data that are given in Table 1, the degrees of freedom equal (n - 2); i.e., the number of observations n less the number of constraints, 1 each for a and b.

In least-squares procedures, the central point of reference for calculating the variance of each variable is its sample mean, which causes the least-squares line to have the property of passing through the means of the variables used to estimate the line. This characteristic is shown in Fig. 1; it can be verified by dividing both sides of the first normal equation by n, since the sample mean of any variable y is

$$\frac{\sum_{i=1}^{n} y_i}{n} = \bar{y}. \tag{5}$$

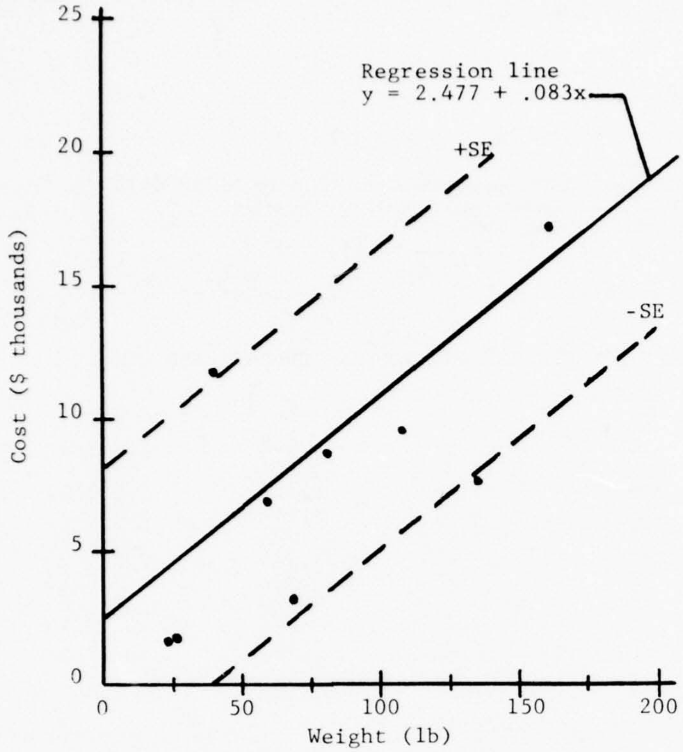


FIG. 2 - REGRESSION LINE AND STANDARD ERROR OF ESTIMATE

By referring to Fig. 1, it can be seen that the total distance from y_i to $\bar{y}$ for any observation on y is the distance from C to B. The sum of all such distances squared and divided by the degrees of freedom is called the total variance of y:

$$\text{Total variance of } y = \Sigma \frac{(y_i - \bar{y})^2}{n - 1} \tag{6}$$

The distance from C to A indicates the amount of the total deviation of $\hat{y}$ from $\bar{y}$ which is explained by the estimating relationship. Consequently, the sum of the distances from $\bar{y}$ to the line, squared and divided by the degrees of freedom, is called the explained variance:

$$\text{Explained variance of } y = \Sigma \frac{(\hat{y}_i - \bar{y})^2}{n - 2} \tag{7}$$

The remaining distance from A to B is the residual or unexplained deviation from y_i to $\bar{y}$, or the unexplained variance:

$$\text{Unexplained variance of } y = \Sigma \frac{(y_i - \hat{y}_i)^2}{n - 2} \tag{8}$$

The standard error of estimate is defined as the square root of the unexplained variance of the y's:

$$SE = \sqrt{\frac{\Sigma (y_i - \hat{y}_i)^2}{n - 2}} \tag{9}$$

For the equation y = 2.477 + 083x, the standard error of estimate is $5,808. This value has been plotted above and below the regression line in Fig. 2. The interpretation and significance of these results will be discussed in connection with the use of prediction intervals.

In comparing one SE with another, it is useful to compute a relative standard error of estimate. One such measure is the coefficient of variation (CV), which relates the SE to the mean of the sample y's:

$$CV = \frac{SE}{\bar{y}}. \tag{10}$$

Continuing the analysis of the data in Table 1, the mean of the y's is $9,060. Therefore, the value of CV is

$$\frac{\$5,808}{\$9,060} = .641.$$

This value is high. Although the question of reliability of an estimating equation is relative to the context in which the equation is to be used, a value at least as small as 10 to 20 percent for the coefficient of variation is desirable.

The standard error of estimate gives a measure of the magnitude of the unexplained variance. Another related measure of dispersion is given by the coefficient of determination that shows the proportion of total variance accounted for by the estimating relationship:

$$r^2 = \text{Coefficient of determination} = \frac{\text{Explained variance}}{\text{Total variance}}$$

$$= 1 - \frac{\text{Unexplained variance}}{\text{Total variance}}. \tag{11}$$

When all the observed points in the sample are on the least-squares line, the coefficient of determination equals 1 and there is no unexplained or residual variance. As the proportion of total variance that remains unexplained increases, the coefficient of determination approaches zero. The square root of the coefficient of determination is called the correlation coefficient. Correlation has no substantive meaning unless both the dependent and explanatory variables are assumed to be normal random variables. The ordinary assumption in using regression analysis for developing estimating relationships is that only the dependent variable is random. Consequently, it is not considered good practice for the correlation coefficient to be used in documenting the results in this particular application of regression analysis. The inclusion of the correlation coefficient, however, causes no serious problem since it is simply the square root of the coefficient of determination. When analysts review the results, they can easily calculate the latter from the former. Since the coefficient of determination is always in the range between zero and one, its square root will always be larger, except at the boundary points of zero and one.

The coefficient of determination for Eq. (4) is .325, which is relatively low and further substantiates the evidence that weight alone is not a good predictor of the cost of airborne radio communication equipment.

PREDICTION INTERVALS: The procedure for calculating the prediction interval for a simple regression is as follows. For a given value of the explanatory variable, say x, the estimating equation is used to obtain a predicted value of the dependent variable:

$$\hat{y} = \hat{a} + \hat{b}x. \tag{12}$$

The prediction interval puts a boundary around $\hat{y}$:

$$\hat{y} \pm A_{\varepsilon/2}. \tag{13}$$

There is a certain level of confidence $(1 - \varepsilon)$ that the cost of a set weighing x will be in that interval.

Values for $\varepsilon/2$ rather than ε are used since $\hat{y}$ is to be bounded on both sides. The values of ε can be divided by two since under the assumptions, the probability distribution about $\hat{y}$ is normal and therefore is symmetrical. In statistical terminology, a two-tailed t distribution for constructing the intervals is used.

In the case of simple regression, a $100(1 - \varepsilon)$ - percent prediction interval for an estimated value of the dependent variable can be constructed as follows:

$$\hat{y} \pm A_{\varepsilon/2}, \tag{14}$$

where

$$A_{\varepsilon/2} = (SE)t_{\varepsilon/2} \sqrt{\frac{n+1}{n} + \frac{(x - \bar{x})^2}{\Sigma (x_i - \bar{x})^2}}, \tag{15}$$

and where SE = the standard error of the estimating equation from which $\hat{y}$ was obtained,

$t_{\varepsilon/2}$ = the value obtained from a table of t-values for the $\varepsilon/2$ significance level,

n = the size of the sample,

x = the specified value of the explanatory variable used as a basis for

obtaining $\hat{y}$,

$\bar{x}$ = the mean of the x's in the sample,

$(x_i - \bar{x})^2$ = the sum of the squared deviations of the sample x's from their sample mean.

When the estimating equation derived previously is used, the cost of a communications set weighing 100 lbs is estimated at \$10,777. To establish around this value a 90-percent prediction interval (i.e., one with a 10-percent level of significance), the necessary data are

$$\begin{aligned} SE &= 5.808, \\ \varepsilon &= 0.1, \\ \varepsilon/2 &= 0.05, \\ t &= 1.86, \\ n &= 10, \\ df &= 8, \\ x &= 100 \text{ lbs}, \\ \bar{x} &= 79.2 \text{ lb}, \\ \Sigma\,(x - \bar{x})^2 &= 18{,}813.6 \text{ lb}. \end{aligned}$$

By substituting these data in Eq. (15), solving for $A_{\varepsilon/2}$, and multiplying by 1000, we obtain

$$A_{\varepsilon/2} = \$11{,}447.$$

Therefore, for x = 100 lb, the 90-percent prediction intervals in dollars are

$$\hat{y} \pm A_{\varepsilon/2} = \$10{,}777 \pm \$11{,}447.$$

The percentage $100(1 - \varepsilon)$ is the confidence level of the prediction intervals, which means that if repeated observations on the cost of communications sets that weigh 100 lb were taken, $100(1 - \varepsilon)$ percent of the time these observations would lie within the range set by the $100(1 - \varepsilon)$ prediction intervals. This is the only sense in which a level of confidence can be associated with prediction intervals. It is erroneous to infer that there is a $100(1 - \varepsilon)$-percent probability that the actual value for any particular case will lie within the interval.

Further, prediction intervals are valid outside the range encompassed by the sample data that are used to generate the estimating relationship and the interval only if the estimating relationship is itself valid outside that range. For example, if there were occasion for the line to curve up or down or if a discontinuity in the form of a discrete jump in cost occurred for weights outside the sample range, this fact would not be reflected in the prediction interval. Thus, it must be clearly indicated when the intervals are used for estimates based on values outside the sample range.

This prediction interval procedure can be repeated for other values of x and the results plotted to obtain a 90-percent prediction interval band around the regression line, as shown in Fig. 3. In this case, the 90-percent confidence region is fairly wide because of the relatively large standard error of this equation. The formula for the prediction interval is such that the width of the interval is sensitive to the size of the standard error; large standard errors indicate that much of the cost variation in the observed data is unexplained by the equation.

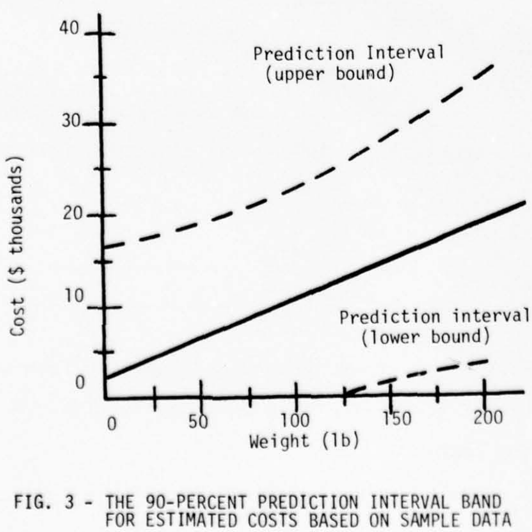


FIG. 3 - THE 90-PERCENT PREDICTION INTERVAL BAND FOR ESTIMATED COSTS BASED ON SAMPLE DATA

TABLE 10
GOODNESS OF FIT RESULTS FOR RELIABILITY COST (Cont'd)

In using regression analysis, it must be noted that the statistical significance of regression relationships does not necessarily imply existence of a causal relationship. The following excerpt from an Institute of Defense Analyses (IDA) memorandum illustrates the importance of this distinction in cost analysis:*

> Frequently during cost effectiveness studies, the distinction between a "causation" cost model and a "correlation" cost model is overlooked. A simple example will be used to illustrate the distinction between the two types of cost models and show how a sensitivity analysis performed with a correlation cost model, rather than a causation model, can lead to erroneous conclusions.
>
> Example: Estimate the cost of assembling a piece of hardware. The assembly consists merely of bolting various elements together. The overwhelming majority of the cost of the assembly process is the salary paid to the men who do the bolting. Careful analysis of all the available cost data might yield a correlation cost model given by Equation 1.

$$C = a \times w \tag{1}$$

where w is the total weight of all the bolts that go into the assembly,
C is the cost of the assembly,
a is a regression coefficient.

By all of the various statistical measures of goodness of fit, Model 1 is a valid prediction equation.

The causation cost model is given by Equation 2.

$$C = k \times h \times n \tag{2}$$

where k is the hourly wages of the assemblers,
h is the number of hours it takes to fasten and bolt,
n is the number of bolts used in the final assembly,
C is the cost of the assembly.

It should be noted that the correlation cost model and the causation model are interrelated by Equation 3.

$$w = B \times n \tag{3}$$

where B is the weight of a single bolt,
w is the total weight of all of the bolts that go into the assembly.

Thus any design or sensitivity analysis performed on Equation 1, the correlation cost model, will lead to the correct results if Equation 3 is not violated. For example, an analyst would be correct in predicting that a cost reduction would occur if he reduced the weight of the fasteners used by using less fasteners. He would be incorrect if he predicted a cost reduction would occur if he reduced the weight of the fasteners by substituting aluminum for steel bolts while keeping the number of bolts constant. The reason that a substitution of aluminum for steel bolts would not reduce the cost, is because the underlying relationship between the number of bolts and the weight of the fasteners (Equation 3), which is the reason for the good cost weight relationship of the correlation model, has been violated.

In mathematical terms both a causation and a correlation cost model have the following properties.

$$\text{Cost} = f\ (\text{characteristics}) \tag{4}$$

But <u>only</u> a causation model can be manipulated as Equation 5.

$$\text{Characteristics} = f^{-1}\ (\text{cost}) \tag{5}$$

The problem of determining whether a cost model is a correlation or a causation model is, except for the trivially simple type of problem illustrated here, very difficult since all causation models can be transformed into correlation models. There exist no statistical tests to determine whether a model is a causation model or a correlation model.

The types of explanatory variables used in the cost model generally will give a good guide as to whether a model is a correlation model or a causation model. For example, weight as an explanatory variable in a cost model where the material cost did not dominate, would be a good indication that the cost model was a correlation model.

If the model is a correlation model and the analyst performs a sensitivity analysis, he runs the risk of violating the unknown underlying relationships between

* Morris Zusman, "Use of Cost Models in Sensitivity Analysis and as a Design Aid," Institute of Defense Analyses, N-587(R), September 1968. In this discussion, the term correlation is used figuratively in the sense that it is statistically significant in explaining the amount of variance rather than in the sense that both the dependent and independent variables are random.

the correlation and causation models. If these underlying relationships are violated the sensitivity analysis will be erroneous.

This example illustrates that regression analysis is an aid to, and not a substitute for, experience and understanding.

The bibliography presents many references on cost estimating relationships (CER's) derived by linear regression. Some of these are almost as simple as the cost to weight relationship, but hopefully more useful. Some require the use of a computer program to handle the large number of variables. The next section will look at the results of some regression models relating acquisition costs and reliability.

Improving reliability is a universally recognized method for reducing O&M costs. However, improving reliability requires an investment during acquisition. To properly trade-off reliability against LCC one must consider both aspects. For this reason, the Rome Air Development Center (RADC), initiated a program for determining the relationship of reliability to acquisition costs, and in the course of that program produced two models concerned with development costs and one concerned with production cost. The first two are based on linear regression and provide examples of its application to cost modeling.

RELIABILITY ACQUISITION COST STUDY: RADC-TR-77-334, "Reliability Acquisition Cost Study" details the efforts performed by the General Electric Aerospace Electronic Systems Department, Utica NY on contract to RADC to provide models relating development costs to reliability.

The objectives of this study were to develop relationships capable of determining and predicting the costs attributable to reliability during the development phase of electronic equipment acquisition. Further, basic relationships were to be developed equating reliability increments to increments in development cost. Specifically, the key objectives identified at the outset of the study were to:

- Develop a relationship between the equipment reliability and the total reliability development cost.
- Develop a relationship between reliability element costs and the equipment reliability.

The study dealt with three reliability elements as they relate to ten equipments from two manufacturers. These elements are:

- Reliability Design Program - including prediction, failure mode and effects analysis (FMEA), and design reviews.
- Reliability Parts Program - including parts screening specification, parts standardization and control, and vendor control.
- Reliability Testing Program - including evaluation testing, equipment environmental screening, and reliability demonstration testing.

The approach to the study was to hypothesize linear models (linear in coefficients but not necessarily linear in the variables) for developing relationships between equipment reliability and reliability cost; collect reliability cost data, reliability data (based on failure rate history) and normalization data on the various equipments; correlate the data; synthesize the data to the models and iterate the models to satisfaction. All of the data analyses were performed using time-share computer programs developed by the Information Services Business Department of the General Electric Company in cooperation with the General Electric Corporate Research and Development Center.

Multiple regression analyses were performed to develop prediction equations for:

- Total reliability cost as a function of resultant equipment MTBF and quantity of parts.
- Reliability prediction cost as a function of quantity of parts.
- Reliability design review cost as a function of quantity of parts.
- Reliability failure modes and effects analysis cost as a function of the prediction cost.
- Reliability design cost as a function of quantity of parts.
- Resultant equipment MTBF as a function of reliability parts program cost, reliability test program cost and quantity of parts.

It should be pointed out that a formal failure modes and effects analysis effort was performed for only three of the equipments in the data base. Therefore, the prediction relationship for failure modes and effects analysis cost, being developed from only three pieces of data, is statistically weaker than the others. Also, since there were only three equipments with FMEA, these equipments were excluded from the develop-

ment of the prediction equation for the reliability design cost.

The prediction equations are:

Total Reliability Cost

$$C_T = 1.804\ \theta_R^{0.370} N_P^{0.684} \tag{1}$$

Reliability Prediction Cost

$$C_{PR} = 119.16 + 0.096N_P \tag{2}$$

Reliability Design Review Cost

$$C_{DR} = 92.479 + 0.022N_p \tag{3}$$

Reliability Failure Modes and Effects Analysis Cost

$$C_{FM} = 0.80\ C_{PR} \tag{4}$$

Reliability Design Cost (by definition)

$$C_d = C_{PR} + C_{DR} + C_{FM} \tag{5}$$

Reliability Design Cost (excluding FMEA)

$$C_d = 242.2 + 0.121N_p \tag{5a}$$

Reliability Parts Program Cost plus Reliability Test Program Cost

$$C_{p+t} = C_T - C_d \tag{6}$$

Resultant Equipment MTBF

$$\theta_R = \frac{5.360C_p^{1.422}C_t^{0.639}}{N_p^{1.372}} \tag{7}$$

A summary of the key statistics for these equations is shown in Table 5 for equations (1), (2), (3), (4), (5a) and (7). Equations (5) and (6) are not included in the summary since they were generated by definition instead of by performing regression analyses.

These equations allow prediction of reliability costs and resultant equipment MTBF's but do not address the question of incremental gain in equipment MTBF as a result of each of the reliability elements. Consequently, they have been termed gross prediction equations.

The statistics provided through the regression analyses give an indication of the accuracy of the equations. As can be seen from Table 3 the index of determination, R^2 indicates that the prediction equations account for more than 50 percent of the initial variation. Also, from Table 3, a comparison of the standard error of estimate, S_E, and the standard deviation, S_Y, indicates that the dependent variable can be predicted more accurately using the equation than by using the mean of the dependent variable.

Also, the adequacy of these prediction equations can be assessed by comparing the values predicted by each equation with the actual data values that were used to develop the relationships (see Table 4).

In addition to percent difference between predicted and actual values, approximate confidence limits about the actual average value can be computed through the use of appropriate factors. Such factors are shown in Table 5, for each of the prediction equations (for 60, 75 and 95% confidence limits). The confidence limits are based on the assumption that the independent variable values for each prediction are equal to the average values of the appropriate variable in the sample.

As can be seen from Table 4, the largest deviation for the predicted values was the reliability prediction cost for radar E which was high by a factor of almost four. Also, the design is high by a factor of three. This results from the fact that the actual reliability prediction and design costs for this equipment are low. The reason they are low is attributed to the fact that this radar was developed in parallel with the digital portion of the same system. This is digital equipment F in the data base. It appears that the radar benefitted from this parallel development, which results in a lower cost

TABLE 3
GROSS PREDICTION EQUATIONS AND STATISTICS SUMMARY

Equation	R	R^2	F Ratio	S_E	S_Y
$C_T = 1.80\,\theta_R^{0.37}\,N_p^{0.68}$	0.978	0.957	99.99	0.180	* 0.759
$C_{PR} = 119.16 + 0.096\,N_p$	0.699	0.488	97.55	679.29	895.54
$C_{DR} = 92.48 + 0.02\,N_p$	0.759	0.576	98.91	132.37	191.70
$C_{FM} = 0.80\,C_{PR}$	0.996	0.992	99.62	160.77	1513.29
$C_d' = 242.2 + 0.121\,N_p$	0.936	0.876	99.80	286.53	740.34
$\theta_R = \dfrac{5.36\,C_p^{1.42}\,C_t^{0.64}}{N_p^{1.37}}$	0.895	0.801	98.43	0.879	* 0.479

* These result from log linear equations.

TABLE 4
COMPARISON BETWEEN PREDICTED COSTS AND ACTUAL COSTS WITH PERCENT DIFFERENCE

		Equipment Letter Code									
		A	B	C	D	E	F	G	H	J	K
C_T	Pred.	21,561	7,636.8	7,352.5	2,925.3	9,026.8	7,077.1	2,391.9	11,621.7	2,664.8	2,817.7
	Act.	23,449	10,264.0	7,719.0	2,976.0	6,776.0	5,883.0	2,645.0	11,947.0	2,532.0	2,795.0
	% Diff.	-8.75	-34.4	-4.98	-1.73	24.93	16.86	-10.58	-2.8	4.98	0.805
C_{PR}	Pred.	1,894.8	1,145.5	1,189.2	371.5	1,806.6	714.7	562.9	1,781.4	411.8	367.7
	Act.	3,165	1,036	761	452.0	487.0	649.0	549.0	2,076.0	547.0	544
	% Diff.	-67.02	9.56	36.01	-21.66	73.04	9.11	2.47	-16.53	-27.98	-47.91
C_{DR}	Pred.	505.3	331.1	341.2	151.1	484.8	231.0	195.6	478.9	160.5	150.2
	Act.	633.6	460.0	326.0	206.0	203.0	131.2	165.0	594.0	148.0	163.0
	% Diff.	-25.39	-38.9	4.45	-36.3	58.22	43.20	15.64	-24.08	7.78	-8.50
C_{FM}	Pred.	2,529.2	-	-	-	389.2	519.1	-	-	-	-
	Act.	2,531.2	-	-	-	203.0	649.0	-	-	-	-
	% Diff.	-0.07	-	-	-	47.84	-25.12	-	-	-	-
C_d	Pred.	4,929.3	1,476.6	1,530.4	522.6	2,680.6	1,464.8	757.9	2,260.3	572.3	517.9
	Act.	6,329.5	1,496.0	1,087.0	658.0	893.0	1,427.0	713.0	2,670.0	675.0	707.0
	% Diff.	-28.40	-1.31	28.97	-25.9	66.68	2.5	5.93	-18.12	-17.95	-36.51
C_d'	Pred.	-	1,537.4	1,592.6	560.7	-	-	802.2	2,340.0	611.5	556.0
	Act.	-	1,496.0	1,087.0	658.0	-	-	713.0	2,670.0	675.1	707.0
	% Diff.	-	2.69	31.75	-17.36	-	-	11.12	-14.10	-10.41	-27.17
C_{p+t}	Pred.	16,631.7	6,160.2	5,849.1	2,402.7	6,346.8	5,612.3	1,634.0	9,361.4	2,092.5	2,299.8
	Act.	17,119.6	8,768	6,632.0	2,318.0	5,883.0	4,456.2	1,932.0	9,277.0	1,856.8	2,088.0
	% Diff.	-2.93	-42.33	-13.38	3.52	7.31	20.59	-18.24	0.90	11.26	9.21
θ_R	Pred.	1,121.2	479.9	181.6	197.3	98.5	289.4	78.6	343.8	127.2	199.3
	Act.	1,350.0	225.0	188.0	225.0	141.0	501.0	46.0	287.0	133.0	207.0
	% Diff.	-20.4	53.1	-3.52	-14.0	-43.16	-73.11	41.51	16.5	-4.5	-4.84

TABLE 5
CONFIDENCE LIMIT APPROXIMATIONS

Multiply the values of C_T and θ_R by the following factors for the Confidence Limit indicated.

PREDICTION VARIABLE	$M_{0.60}$		$M_{0.75}$		$M_{0.95}$	
	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER
C_T	.05	1.05	.93	1.07	.87	1.14
θ_R	.78	1.28	.71	1.41	.52	1.9

Add (subtract) from the values of C_{PR}, C_{DR}, C_d^I the indicated values.

PREDICTION VARIABLE	$M_{0.60}$		$M_{0.75}$		$M_{0.95}$	
	LOWER	UPPER	LOWER	UPPER	LOWER	UPPER
C_{PR}	-191	+191	-263	+263	-495	+495
C_{DR}	- 37	+ 37	- 51	+ 51	- 96	+ 96
C_d^1	- 81	+ 81	-111	+111	-208	+208

in prediction and design due to commonality of tasks. If equipment E is excluded from the reliability prediction analysis, the index of determination, R^2, increases from 0.488 to 0.812 and the standard error of estimate decreases from 679.29 to 430.05.

All of the other prediction quations yield predicted values that are from 0.5 to 2 times the actual values. It is felt that this is acceptable for initial estimates based on the limited data base available coupled with general equipment development uncertainty.

Equation (1) is used to predict the total reliability program cost, C_T. θ_R as used in the equation is the final equipment MTBF requirement in hours converted to a 60 percent lower confidence level and N_p is an estimate of the number of electrical components that the equipment will contain (if the equipment is a modified design, only the new components are used). Putting this information into the equation, one will obtain a prediction in terms of a cost normalized to a new design, airborne, analog configuration. If the equipment is expected to be predominantly analog, this normalized cost, C_T, will be the actual predicted total reliability program cost in mandays.

Equations (2) and (3) are used to estimate the reliability prediction cost, C_{PR}, and the reliability design review cost, C_{DR}, respectively using the number of electrical parts, N_p. The intercepts of these equations represent the fixed cost portion of these reliability element costs.

Equation (4) gives a prediction of the reliability failure modes and effects analysis cost, C_{FM}, if it is required on the equipment, in terms of the effort expended in reliability prediction C_{PR}. This predicted cost, C_{FM}, is also normalized as described above. Equation (4) was developed using the actual prediction data on the 10 equipments of the study, and in the application of the equations, one uses the predicted reliability prediction cost from equation (2) as the value for C_{PR} in equation (4).

Equation (5) yields a normalized predicted cost, C_d, for the reliability design program. This equation was defined using the actual data collected and in application yields a normalized predicted reliability design program cost by adding up the predicted values obtained from equations (2), (3) and (4). If the equipment for which costs are being predicted does not have a failure modes and effects analysis requirement, then equation (4) is not used and the last term of equation (5) is zero. Also, if there is no FMEA, equation (5a) can be used to predict the design cost.

Equation (6) yields a normalized predicted cost for the combined reliability parts and reliability test programs. Again, since this equation was developed from the actual data, the output from equation (5) subtracted from the output of equation (1) will yield a normalized predicted cost for the reliability parts and test programs combined. To obtain the actual cost for digital equipments, the parts portion must be divided by an appropriate "K" factor.

Equation (7) is used to predict the resultant equipment MTBF (at lower 60 percent confidence level) in terms of the normalized reliability parts program cost, the normalized reliability test program cost and the quantity of electrical parts. The procedure for using this equation is to first take the outputs from the other equations

to determine the combined cost for the reliability parts and test program. Next, use equation (7) to determine the allocation of this cost between the parts program and test program. This allocation reflects the average of the actual allocation of the ten equipments in the data base and not the most optimum allocation.

The study included more details, such as the modification of the formulas to cover digita' components and the optimization of costs between the three reliability elements, but the discussion above should suffice to illustrate the use of regression analysis to develop the relationship between reliability and development cost.

RELIABILITY VS ACQUISITION COST (II): The General Electric study was performed on avionic equipment. Following this, RADC awarded a contract to the Hughes Aircraft Company, Ground Systems Group, Fullerton CA for a similar study on ground and shipboard electronic equipment. The final report, "RADC-TR-75-270 - Reliability Acquisition Cost Study (II)", provides more insight into the variations and complexities of regression analysis, and excerpts from this report follow.

SUMMARY OF DATA: The data for the systems investigated for the study comprise two categories. The first category contains system characterization and reliability data. This data gathered on each system expresses the type and function of the system, the reliability values in terms of mean time between failure (MTBF) for the contractual specified ($\theta_o = \theta_{spec}$), the design predicted (θ_{pred}), and the demonstrated (θ_{demo}) reliability values, and the system complexity as defined by the number of total parts (N). The number of parts excludes hardware and equipment that had no direct effect on the system reliability.

The number of parts was also represented by the total number of system analog parts (N_A) and the total number of system digital parts (N_D). This data is summarized in the System Characterization Table, Table 6. The second category contains the reliability cost data. The reliability program was defined by determining the reliability program phases (see Section 2.4.1) and grouping the reliability program costs under the three program phases. The reliability program phase costs are the reliability design phase costs (C_D), the reliability parts phase costs (C_P), and the reliability evaluation phase costs (C_E). The total reliability program costs (C_T) are the summation of the three reliability program costs and all cost values are expressed in mandays. This data is summarized in the Reliability Program Phase Costs Table, Table 7.

TABLE 6
SYSTEM CHARACTERIZATION DATA

System Number	Type or Application	Mean Time Between Failures (Hours)			Total Parts
		Specified	Predicted	Demonstrated	
1	Shipboard ECM System	90	98	183	42901
2	Shipboard Target Acquisition System	125	146	81 (2)	46863
3	Shipboard Radar System Solid State Receiver	500	574	300 (1)	11313
4	Submarine Fire Control Display	290	270	851	21683
5	Low Frequency Sonar with Towed Array System	182	165	264	49243
6	Complex Portable Tracking and Control Center	190	210	266	36493
7	Artillery Locating Radar	250	216	216	18469
8	2400 Bit Per Second Modem	4000	5721	2005 (1)	1031
9	Tank Fire Control Ballistics Computer System	184	369	265	1751
10	Satellite Communications System	200	217.5	173	17108

(1) Reliability Demonstration Test terminated at minimum acceptable time with no failures.
(2) Reliability Demonstration Test conducted by U.S.N. personnel.

TABLE 7
RELIABILITY PROGRAM PHASE COSTS

System Number	Design Phase C_D (man-days)	Parts Phase C_P (man-days)	Evaluation Phase C_E (man-days)	Total C_T (man-days)
1	214	4962	2498	7674
2	244	5301	2196	7741
3	202	4093	2249	6544
4	207	4467	2464	7138
5	237	3580	1348	5165
6	204	7233	9262	16699
7	170	1612	530	2312
8	119	3396	1452	4967
9	272	1252	928	2452
10	148	1449	2110	3707

DEFINITIONS:

C_D - Reliability design phase cost (in man-days)

C_D' - Relative reliability design phase cost, $C_D' = C_D/C_T$

C_E - Reliability evaluation phase cost (in man-days)

C_E' - Relative reliability evaluation phase cost, $C_E' = C_E/C_T$

C_P - Reliability parts phase cost (in man-days)

C_P' - Relative reliability parts phase cost, $C_P' = C_P/C_T$

C_T - Total cost of reliability program (in man-days)

G_D - Reliability gain due to reliability design effort, $G_D = \theta_D/\theta_I$

G_E - Reliability gain due to reliability evaluation effort, $G_E = \theta_E/\theta_P$

G_P - Reliability gain due to reliability parts effort, $G_P = \theta_P/\theta_D$

G_T - Reliability gain due to total reliability program, $G_T = G_D G_P G_E = \theta_E/\theta_I$

k-factor - Adjustment factor for environmental applications

N - Total number of digital and analog parts, $N = N_A + N_D$

N_A - Total number of system analog parts

N_D - Total number of system digital parts

N_{EA} - Number of system parts normalized to analog

θ_D - Post design MTBF (in hours)

θ_E - Post evaluation MTBF (in hours)

θ_I - Initial system MTBF without reliability enhancement (in hours)

θ_P - Post parts MTBF (in hours)

θ_{pred} - Predicted MTBF (in hours)

θ_{spec} - Specified MTBF (contractual) (in hours)

$$\bar{R} = \left(\sum_{i=1}^{n} \left| \frac{Y_i - \hat{Y}_i}{Y_i} \right| \cdot \frac{1}{n} \right) \cdot 100$$

$$R.E. = \frac{\sum_{i=1}^{n} \left((Y_i - \hat{Y}_i)^2 \Big/ (n-2) \right)}{\sum_{i=1}^{n} \left((Y_i - \bar{Y}_i)^2 \Big/ (n-1) \right)}$$

$$\bar{Y}_i = \sum_{i=1}^{n} Y_i \Big/ n$$

where

Y_i = the i^{th} observed value of a particular function.

$\hat{Y}_i$ = the i^{th} calculated value of a particular function (calculated from a model).

n = number of observations.

DATA NORMALIZATION: There are usually a number of independent variables that can affect a given dependent variable. In this study we will particularly be investigating, as dependent variables, reliability and cost. The important, useful independent variables are included in the regression models. However, there are several (independent) variables that may affect the dependent variables which we do not particularly want to include. These will be "normalized" out or excluded from the regression model. These variables are:

- Complexity
- Design differences
- Environmental differences
- Time differences
- Non-relevant cost differences

In this study complexity was measured by parts count. The variable N (total parts count) and (N_A, N_D) were included in the regression models. To be "on the safe side" the digital parts count (N_D) on each system was converted to equivalent analog parts count and a new independent variable, N_{EA}, the total number of equivalent analog parts was included in the regression models. The conversion factor used was a constant $2 \times N_D = N_A$ (two times the number of digital parts equals their equivalent number of analog parts).

The design effects are considered to be negligible because all ten (10) systems in the data base were designed by the Hughes Aircraft Company, nine of these systems were designed at Hughes-Fullerton.

The environmental differences were removed from the MTBF's by normalization. This normalization was important only when predicted or specified MTBF was used as a dependent variable. Also, when ratios (say $\theta_{spec}/\theta_{pred}$) were used as dependent variables the normalization factor was not needed because it cancelled out. The basis for the normalization is given in Table 3.1.1. The k-factors were developed using the fixed ground environment as the normal (k factor = 1) case. The k-factors are composites of the various environmental factors given in MIL-HDBK-217B for the various parts. The weights assigned were based on rough estimates of part distribution. It turned out that the shipboard and ground mobile factors were identical.

The ten (10) systems forming the data base are of relatively recent vintage so that time effects are considered negligible. Finally, to remove non-relevant cost differences (e.g., the changing value of the dollar) all costs are measured in man-days.

TABLE 8
k-FACTORS FOR ENVIRONMENTAL NORMALIZATION

Sys. #	Environment	θ'_{spec}	θ'_{pred}	k-factor	adjusted (θx k-factor) θ_{spec}	adjusted (θx k-factor) θ_{pred}
1	Shipboard	90	98	4	360	392
2	Shipboard	125	146	4	500	584
3	Shipboard	500	574	4	2000	2296
4	Shipboard	290	270	4	1160	1080
5	Shipboard	182	165	4	728	660
6	Ground, Fixed	190	210	1	190	210
7	Ground, Fixed	250	216	1	250	216
8	Ground, Fixed	4000	5721	1	4000	5721
9	Ground, Mobile	184	369	4	736	1476
10	Ground, Mobile	200	217.5	4	800	868

THE REGRESSION VARIABLES: The various sets of dependent and independent variables, 60 in all, are shown in Table 9. Each set was run on each of the five model types discussed in the next section with the exception that in a very few cases where there existed a large number of independent variables (e.g. 3) and a small number of data sets (as in the gain analysis) the second degree model with cross-product terms could not be run because the degrees-of-freedom were to small. Not all of the independent variable sets provided good predictions for the various dependent variables so the list in Table 9 gives all those sets tried, not the sets that were good fits.

For all sets the dependent variable is always cost. The independent variable(s) are those that would normally be available, at least in estimated form, early enough to be of use in predicting costs.

DESCRIPTION OF THE MODELS AND MEASURES OF FIT: Each of the following five models was fitted to each of the variable sets which are seen depicted in Table 9. It was not expected, nor even desired, that all models would fit all the variable sets. Nor was it desired that there be at least one good model fit on every variable set. All that is needed is that there be at least one good model for each dependent variable of interest. For example, in Table 9, the variable sets include 15 with C_T as the dependent variable. As a worst case we only need one model to be a good fit to one of these 15 variable sets with C_T as the dependent variable. The five models used are (ε represents the random error term):

Linear $\quad Y = a_0 + a_1X_1 + \ldots + a_nX_n + \varepsilon$

Ln-Linear $\quad \ln Y = \ln a_0 + a_1\ln X_1 + \ldots + a_n\ln X_n + \varepsilon$

Exponential $\quad Y = e^{(a_0 + a_1X_1 + \ldots + a_nX_n + \varepsilon)}$

Second Degree $\quad Y = a_0 + a_{11}X_1 + a_{12}X_1^2 + \ldots + a_{n1}X_n + a_{n2}X_n^2 + \varepsilon$

Second Degree with Cross Products (example, for n = 2)

$$Y = a_0 + a_{11}X_1 + a_{12}X_1^2 + a_{21}X_2 + a_{22}X_2^2 + a_{(12)}X_1X_2 + \varepsilon$$

TABLE 9
THE REGRESSION VARIABLES

Selection No	Dependent Variable	Independent Variable(s)
1-1	C_T	$\Theta_{spec}/\Theta_{pred}$
1-2	C_T	Θ_{spec}
1-3	C_T	Θ_{pred}
1-4	C_T	N
1-5	C_T	N_{EA}
1-6	C_T	N_A, N_D
1-7	C_D	$\Theta_{spec}/\Theta_{pred}$
1-8	C_D	Θ_{spec}
1-9	C_D	Θ_{pred}
1-10	C_D	N
1-11	C_D	N_{EA}
1-12	C_D	N_A, N_D
1-13	C_P	$\Theta_{spec}/\Theta_{pred}$
1-14	C_P	Θ_{spec}
1-15	C_P	Θ_{pred}
1-16	C_P	N
1-17	C_P	N_{EA}
1-18	C_P	N_A, N_D
1-19	C_E	$\Theta_{spec}/\Theta_{pred}$
1-20	C_E	Θ_{spec}
1-21	C_E	Θ_{pred}
1-22	C_E	N
1-23	C_E	N_{EA}
1-24	C_E	N_A, N_D
1-25	C_T	$\Theta_{spec}/\Theta_{pred}$, N
1-26	C_T	$\Theta_{spec}/\Theta_{pred}$, N_{EA}
1-27	C_T	$\Theta_{spec}/\Theta_{pred}$, N_A, N_D
1-28	C_T	Θ_{spec}, N
1-29	C_T	Θ_{spec}, N_{EA}
1-30	C_T	Θ_{spec}, N_A, N_D
1-31	C_T	Θ_{pred}, N
1-32	C_T	Θ_{pred}, N_{EA}
1-33	C_T	Θ_{pred}, N_A, N_D
1-34	C_D	$\Theta_{spec}/\Theta_{pred}$, N
1-35	C_D	$\Theta_{spec}/\Theta_{pred}$, N_{EA}
1-36	C_D	$\Theta_{spec}/\Theta_{pred}$, N_A, N_D

TABLE 9
THE REGRESSION VARIABLES (Cont'd)

Selection No	Dependent Variable	Independent Variable(s)
1-37	C_D	Θ_{spec}, N
1-38	C_D	Θ_{spec}, N_{EA}
1-39	C_D	Θ_{spec}, N_A, N_D
1-40	C_D	Θ_{pred}, N
1-41	C_D	Θ_{pred}, N_{EA}
1-42	C_D	Θ_{pred}, N_A, N_D
1-43	C_P	$\Theta_{spec}/\Theta_{pred}$, N
1-44	C_P	$\Theta_{spec}/\Theta_{pred}$, N_{EA}
1-45	C_P	$\Theta_{spec}/\Theta_{pred}$, N_A, N_D
1-46	C_P	Θ_{spec}, N
1-47	C_P	Θ_{spec}, N_{EA}
1-48	C_P	Θ_{spec}, N_A, N_D
1-49	C_P	Θ_{pred}, N
1-50	C_P	Θ_{pred}, N_{EA}
1-51	C_P	Θ_{pred}, N_A, N_D
1-52	C_E	$\Theta_{spec}/\Theta_{pred}$, N
1-53	C_E	$\Theta_{spec}/\Theta_{pred}$, N_{EA}
1-54	C_E	$\Theta_{spec}/\Theta_{pred}$, N_A, N_D
1-55	C_E	Θ_{spec}, N
1-56	C_E	Θ_{spec}, N_{EA}
1-57	C_E	Θ_{spec}, N_A, N_D
1-58	C_E	Θ_{pred}, N
1-59	C_E	Θ_{pred}, N_{EA}
1-60	C_E	Θ_{pred}, N_A, N_D

GOODNESS OF FIT OF MODELS: For applications of the results of this study only one of the above models is needed for any particular set of variables (Y, X_1, ..., X_n). Also, it is of interest to see, over a variety of situations, whether one particular model is invariably, or even frequently, the best fitting model.

Because of the absurdity of the assumption that any particular data set (of dependent and some independent variables) is a random sample from a multivariate normal distribution, the usual measures of goodness of fit (F test, t test and Correlation) have been abandoned. The two measures of goodness of fit which we have selected are $\overline{R}$ and R.E.. The formal definitions of these quantities were given in a previous section. In words, $\overline{R}$ measures the average (arithmetic mean) absolute value of the relative (to the observed values) deviation of the observed and calculated (from the model) values of the dependent variable. R.E. measures the fraction of the unexplained variation to the total variation. The smaller the values of $\overline{R}$ and R.E. for a particular data set the better the fit. The ideal, but impossible, situation would be $\overline{R} = 0$ and R.E. = 0.

MULTIPLE LINEAR REGRESSION METHODOLOGY: Given a linear equation in two variables, $Y = \alpha + \beta X$ where α is the Y intercept and β is the slope of the line, the problem of finding the "best fit" line to a given set of N points (x_1, y_1), (x_2, y_2), ... , (x_N, y_N) is to determine the values a and b so that the sum of the squares of the difference between the estimated values of Y (given by $\hat{Y} = a + bX$) and the observed

values of Y is a minimum. This is the least squares approach.

The constants a and b of the equation $\hat{Y} = a + bX$ are solutions of two linear equations called normal equations.

$$aN + b\sum_{i=1}^{N} X_i = \sum_{i=1}^{N} Y_i$$

$$a\sum_{i=1}^{N} X_i + b\sum_{i=1}^{N} X_i^2 = \sum_{i=1}^{N} X_i Y_i .$$

The constants a and b are given by

$$b = \frac{N\sum_{i=1}^{N} X_i Y_i - \sum_{i=1}^{N} X_i \sum_{i=1}^{N} Y_i}{N\sum_{i=1}^{N} X_i^2 - \left(\sum_{i=1}^{N} X_i\right)^2}$$

and

$$a = \overline{Y} - b\overline{X}$$

where $\overline{X}$ is the mean of the X-values and $\overline{Y}$ is the mean of the Y-values.

In the multivariable case the normal equations are similar to the linear case. The Y-values are the dependent variables, i.e., in the analysis of the data the dependent variables can be reliability phase cost or total cost, and the X-values are the independent variables, i.e., number of system parts, reliability phase costs, system MTBF's, depending on the relationship that is being analyzed.

New software was created to calculate the deviation (error) from the regression analysis data. The measures of "goodness of fit" (R.E. and $\overline{R}$) were determined for each selection for all models and sorted for the "best fit" by selection number.

RESULTS OF DATA ANALYSES: The variable sets as previously mentioned, all have reliability cost, in some form or other, as the dependent variable. The distribution of the sixty sets (selections) is

SELECTION NUMBERS	DEPENDENT VARIABLE
1-1 through 1-6	C_T
1-25 through 1-33	C_T
1-7 through 1-12	C_D
1-34 through 1-42	C_D
1-13 through 1-18	C_P
1-43 through 1-51	C_P
1-19 through 1-24	C_E
1-52 through 1-60	C_E

The results of the model fits are given, by model, in Table 10. In the following sections we discuss the best fit results for each individual cost category and total costs.

Results for total cost, C_T

$$C_T = -24{,}814 + 41.30\,\theta_{spec} - 0.00810\theta_{spec}^2 + 1.89N_A - 0.000015N_A^2$$

n = the size of the sample,

x = the specified value of the explanatory variable used as a basis for

$$+0.40N_D + 0.0000082N_D^2 - 0.0013N_A\,\theta_{spec} - 0.0032N_D\,\theta_{spec}. \quad (1)$$

$$C_T = -28,154 + 24.850\theta_{pred} - 0.0032\theta_{pred}^2 + 2.34N_A - 0.000027N_A^2$$

$$+0.76N_D - 0.000061N_D^2 - 0.0011N_A\theta_{pred} - 0.00064N_D\,\theta_{pred}. \quad (2)$$

TABLE 10
GOODNESS OF FIT RESULTS FOR RELIABILITY COST

	Linear		Ln-Linear		Expon		2nd Deg		2nd Deg CP	
Selection	R.E.	$\overline{R}$	R.E.	$\overline{R}$	R.E.	$\overline{R}$	R.E.	$\overline{R}$	R.E.	$\overline{R}$
1-1	1.12	56.27	1.17	46.93	1.19	48.06	0.75	35.04	0.75	35.04
1-2	1.08	60.13	1.09	51.39	1.18	52.92	1.01	61.54	1.01	61.54
1-3	1.07	59.44	1.07	51.63	1.20	56.42	0.98	58.23	0.98	58.23
1-4	0.88	47.54	0.95	43.61	0.95	40.93	0.81	45.97	0.81	45.97
1-5	0.87	48.22	0.95	43.35	0.93	41.07	0.84	47.46	0.84	47.46
1-6	0.86	48.80	0.93	42.26	0.92	41.21	0.75	44.60	0.61	37.68
1-7	1.09	19.31	1.09	19.74	1.87	27.64	0.98	19.73	0.98	19.73
1-8	0.76	15.51	1.03	19.47	6.21	45.42	0.69	12.43	0.69	12.43
1-9	0.81	15.07	1.09	19.38	5.01	39.28	0.62	12.99	0.62	12.99
1-10	0.94	16.08	1.05	15.92	0.95	15.25	0.85	15.27	0.85	15.27
1-11	0.97	16.86	1.07	16.48	0.98	16.23	0.88	16.40	0.88	16.40
1-12	0.90	15.31	0.61	12.84	0.92	14.91	0.76	13.84	0.65	10.49
1-13	1.10	60.27	1.17	53.80	1.20	55.33	0.67	40.02	0.67	40.02
1-14	1.11	64.26	1.17	59.26	1.22	56.68	1.05	64.85	1.05	64.85
1-15	1.10	64.68	1.13	59.47	1.19	58.38	1.02	62.70	1.02	62.70
1-16	0.73	49.06	0.87	49.95	0.80	44.78	0.72	49.26	0.72	49.26
1-17	0.72	49.31	0.87	49.84	0.77	43.82	0.72	49.24	0.72	49.24
1-18	0.72	49.53	0.86	49.25	0.78	44.22	0.63	43.35	0.41	32.60
1-19	1.12	82.39	1.20	59.16	1.18	61.43	0.88	55.40	0.88	55.40
1-20	1.05	92.76	1.10	62.94	1.19	69.12	0.98	100.00	0.98	100.00
1-21	1.05	90.83	1.11	62.65	1.21	73.22	0.97	99.12	0.97	99.12
1-22	1.02	73.05	1.08	54.48	1.11	55.63	0.90	87.73	0.90	87.73
1-23	1.01	73.14	1.08	53.87	1.09	55.89	0.93	86.93	0.93	86.93
1-24	0.99	74.18	1.06	52.33	1.08	55.36	0.83	91.90	0.76	76.93
1-25	0.85	47.73	0.86	41.80	1.33	74.26	0.50	31.48	0.45	30.76
1-26	0.84	48.47	0.86	41.38	1.09	60.97	0.50	31.26	0.49	30.61
1-27	0.84	48.59	0.83	41.36	1.14	64.49	0.38	27.84	0.11	15.51
1-28	0.88	42.38	1.04	38.24	1.03	33.03	0.69	47.76	0.46	37.51
1-29	0.86	41.73	1.04	37.68	0.99	32.88	0.74	48.02	0.33	32.92
1-30	0.85	41.92	1.02	36.22	0.98	33.16	0.61	45.44	0.00	1.15

TABLE 10
GOODNESS OF FIT RESULTS FOR RELIABILITY COST (Cont'd)

	Linear		Ln-Linear		Expon		2nd Deg		2nd Deg CP	
Selection	R.E.	$\overline{R}$	R.E.	$\overline{R}$	R.E.	$\overline{R}$	R.E.	$\overline{R}$	R.E.	$\overline{R}$
1-31	0.88	42.73	1.06	35.52	1.01	34.37	0.71	44.46	0.21	17.85
1-32	0.86	42.51	1.05	34.71	0.98	34.70	0.77	43.56	0.15	20.59
1-33	0.85	43.01	1.03	32.76	0.97	34.88	0.62	42.88	0.01	6.05
1-34	0.71	16.04	0.54	14.16	14.55	79.62	0.31	10.83	0.31	10.77
1-35	0.78	16.68	0.62	14.99	9.99	64.78	0.36	11.95	0.36	11.93
1-36	0.60	14.69	0.11	6.23	28.67	100.00	0.16	6.60	0.15	6.75
1-37	0.75	15.32	1.02	17.91	4.08	36.57	0.24	8.43	0.24	8.24
1-38	0.76	15.51	1.03	18.51	4.92	39.57	0.24	8.18	0.24	8.31
1-39	0.66	13.90	0.45	12.48	5.67	43.24	0.24	8.75	0.11	5.86
1-40	0.80	14.96	1.05	16.77	3.44	32.68	0.18	6.75	0.15	6.00
1-41	0.81	15.11	1.07	17.69	4.11	35.59	0.19	7.19	0.19	7.15
1-42	0.73	14.24	0.54	13.20	4.22	36.08	0.22	7.59	0.11	5.14
1-43	0.70	48.97	0.81	49.18	0.75	45.19	0.46	32.93	0.46	32.62
1-44	0.70	49.75	0.81	48.94	0.44	44.68	0.49	33.20	0.49	33.16
1-45	0.70	49.51	0.79	47.87	0.74	44.89	0.27	27.95	0.09	11.65
1-46	0.64	34.23	0.96	42.27	0.88	31.38	0.53	41.08	0.37	33.75
1-47	0.61	33.94	0.95	41.99	0.77	30.01	0.57	38.75	0.35	30.48
1-48	0.60	34.45	0.92	41.14	0.77	30.33	0.40	34.45	0.03	9.39
1-49	0.64	36.28	0.93	40.41	0.86	33.15	0.51	36.70	0.16	18.31
1-50	0.62	36.75	0.93	39.95	0.77	32.75	0.56	34.76	0.20	20.70
1-51	0.62	37.09	0.90	38.70	0.79	32.54	0.38	31.66	0.01	3.73
1-52	0.99	71.79	1.00	54.93	2.83	100.00	0.58	53.80	0.48	56.85
1-53	0.98	71.56	0.99	54.52	2.39	100.00	0.50	47.11	0.46	56.26
1-54	0.98	72.37	0.97	52.24	2.02	100.00	0.49	45.99	0.11	28.70
1-55	1.01	82.37	1.12	50.69	1.14	52.63	0.79	100.00	0.54	73.78
1-56	1.00	81.02	1.12	49.54	1.13	52.30	0.82	100.00	0.30	64.67
1-57	0.99	80.43	1.10	47.45	1.12	51.77	0.73	100.00	0.01	13.69
1-58	1.01	79.87	1.15	46.30	1.13	53.68	0.85	95.76	0.31	41.05
1-59	1.00	78.79	1.15	44.67	1.12	53.57	0.88	96.79	0.15	41.15
1-60	0.99	79.09	1.13	43.53	1.11	53.18	0.78	94.26	0.06	27.96

Results for Design Cost, C_D

The best fit results for C_D indicate that virtually all the independent variables are good predictors of C_D. Furthermore, inspection of Table 10 indicates that all of the models do a reasonably good job of fitting. One example of such a model is:

$$C_D = 195.24 + .11\ O_{SPEC} - .000032\ (O_{SPEC})^2 + .023\ N_A$$
$$- 15 \times 10^{-8}\ (N_A)^2 - .094\ N_D + 35 \times 10^{-7}\ (N_D)^2 - 18 \times 10^{-6}\ O_{SPEC}\ .N_A$$
$$+ 48 \times 10^{-6}\ O_{SPEC}\ .N_D$$

Results for part cost, C_P

No one independent variable does well as a predictor for C_P. However, again, the sets of independent variables θ_{spec}, N_A, N_D (1-48) and θ_{pred}, N_D (1-51) are good predictors of C_P. These equations are given below.

$$C_P = -9,133 + 15.02\theta_{spec} - 0.0029\theta^2_{spec} + 1.10N_A - 0.000010N_A^2$$

$$-1.07N_D + 0.000049N_D^2 - 0.00063N_A\,\theta_{spec} - 0.00044N_D\,\theta_{spec} \qquad (3)$$

$$C_P = -11,603 + 10.08\theta_{pred} - 0.0013\theta^2_{pred} + 0.92N_A - 0.000011N_A^2$$

$$+ 0.52N_D - 0.000021N_D^2 - 0.00031N_A\theta_{pred} - 0.00061N_D\,\theta_{pred} \qquad (4)$$

Results for evaluation cost, C_E

None of the single (independent) variable cases provided suitable fits. Again, the independent variables θ_{spec}, N_A, N_D and θ_{pred}, N_A, N_D provide satisfactory fits for the 2nd degree cross products model. These equations (selections 1-57 and 1-60) are given below.

$$C_E = -17,137 + 28.17\theta_{spec} - 0.0056\theta^2_{spec} + 0.79N_A - 0.0000048N_A^2$$

$$+1.78N_D - 0.000051N_D^2 - 0.00067N_A\theta_{spec} - 0.0031N_D\theta_{spec} \qquad (5)$$

$$C_E = -18,027 + 15.77\theta_{pred} - 0.0021\theta^2_{pred} + 1.49N_A - 0.000017N_A^2$$

$$+0.41N_D - 0.000048N_D^2 - 0.00080N_A\,\theta_{pred} - 0.00014N_D\,\theta_{pred}. \qquad (6)$$

<u>Examples</u> (The systems used in the examples were randomly selected)

1) Predicting total cost C_T:

System No. 6 has

$\theta_{spec} = 190$

$\theta_{pred} = 210$

$N_A = 28,429$

$N_D = 8,064$

$C_T = 16,699.$

Using equation (1) we obtain

$$C_T = -24,814 + 41.30(190) - 0.0081(190)^2 + 1.89(28,429)$$
$$-0.000015(28,429)^2 + 0.40(8,064) - 0.0000082(8,064)^2$$
$$-0.0013(190)(28,429) - 0.0032(190)(8,064)$$
$$= 16,466.53$$

which is in close agreement with $C_T(OBS) = 16,699$. Also, equation (2) leads to

$$C_T = -28,154 + 24.85(210) - 0.0032(210)^2 + 2.34(28,429)$$
$$-0.000027(28,429)^2 + 0.76(8,064) - 0.000061(8,064)^2$$
$$-0.0011(210)(28,429) - 0.00064(210)(8,064)$$
$$= 16,137.65.$$

2) Predicting design cost C_D:

System No. 1 has

$\theta_{spec} = 360$

$\theta_{pred} = 392$

$N_A = 28,097$

$N_D = 14,804$

$C_D = 214.$

To avoid repetition we will use just the set θ_{spec}, N_A, N_D. From (1-39)

$$C_D = 195.24 + 0.11(360) - 0.000032(360)^2 + 0.023(28,097) - 0.00000015$$
$$\times(28,097)^2 - 0.094(14,804) + 0.0000035(14,804)^2 - 0.000018(360)$$
$$\times 28,097 + 0.000048(360)(14,804)$$
$$= 207.71$$

This agress very well with the C_D(OBS) = 214

3) Predicting part cost C_P:

System No. 3 has

$\theta_{spec} = 2,000$

$\theta_{pred} = 2,296$

$N_A = 9,461$

$N_D = 1,852$

$C_P = 4,093.$

Equation (3) gives

$$C_P = -9,133 + 15.02(2,000) - 0.0029(2,000)^2 + 1.10(9,461)$$
$$-0.000010(9,461)^2 - 1.07(1,852) + 0.000049(1,852)^2$$
$$-0.00063(2,000)(9,461) - 0.00044(2,000)(1,852)$$
$$= 3,454.80.$$

This result agrees well with C_P(OBS) = 4,093.

4) Predicting evaluation cost C_E:

System No. 4 has

$\theta_{spec} = 1,160$

$\theta_{pred} = 1,080$

$N_A = 19,567$

$N_D = 2,116$

$C_E = 2,464.$

Using Equation (5)

$$C_E = -17,137 + 28.17(1,160) - 0.0056(1,160)^2 + 0.79(19,567)$$
$$-0.0000048 \times (19,567)^2 + 1.78(2,116) - 0.000051(2,116)^2$$
$$-0.00067(1,160)(19,567) - 0.0031 \times (1,160)(2,116)$$
$$= 2,346.55.$$

RELIABILITY TRADE-OFFS FOR UNIT PRODUCTION COST: We've spent a lot of time on regression analysis because it is important for the user to understand its difficulties as well as its advantages. The final RADC study in reliability and acquisition cost did not develop regression equations and hence, provides a sample of an alternate means of cost estimating in acquisition.

The study was performed for RADC by the Martin-Marietta Corporation, Orlando FL. At this writing (January 1979) the final report, "Reliability Trade-Offs for Unit Production Cost" is still in printing. Excerpts follow:

A model that relates reliability achievement to the many program trade-offs and their resultant cost consequences should delineate physical, measurable tasks or accomplishments and be subdivided along lines that are traditional for cost collection and reporting. The entire life cycle of the product should be represented.

Below is a general expression for electronic equipment reliability that reflects three primary influences: development engineering, manufacturing, and field use and support.

$$R = MTBF_p \, (R_g) \, (R_m) \, (R_s + R_f + R_d)$$

where

R = mean time between failures at any given time

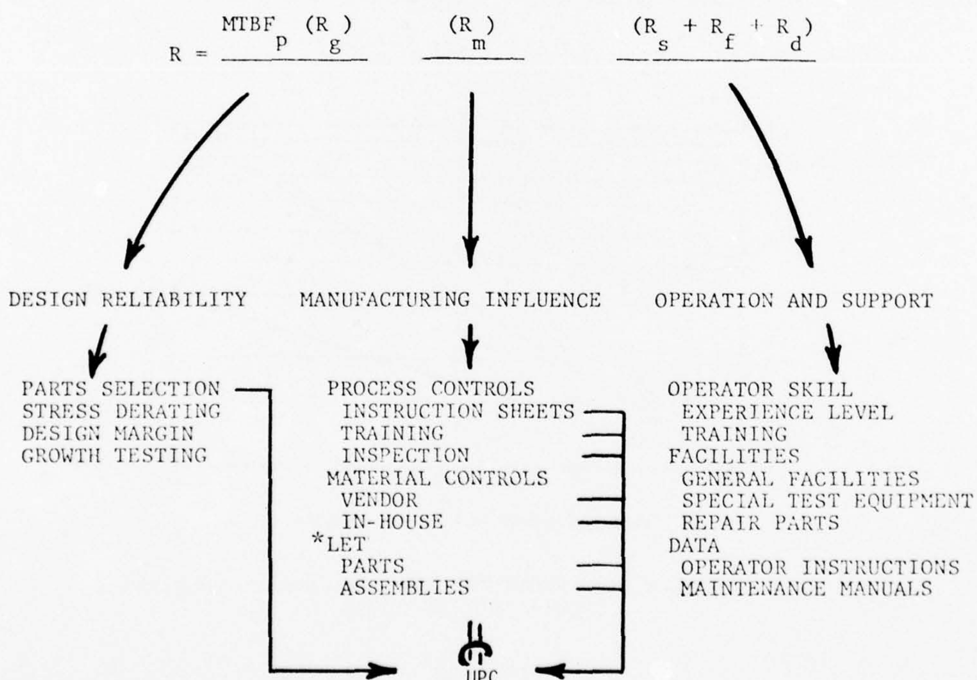
$MTBF_p$ = predicted mean time between failures in accordance with procedures in MIL-HDBK-217. This parameter implicitly accounts for the quality of purchased parts and the electrical and environmental stress and derating.

R_g = reliability growth. This factor generally varies between 0.1 and 1.0 and relates to the adequacy of the test-analyze-fix program during engineering development. A good program will result in a value of R_g equal to 0.9 or greater after about 10,000 hours.

R_m = manufacturing influence. This factor relates to the assurance that any manufacturing induced defects have been detected and removed.

$R_s + R_f + R_d$ = post deployment logistic support influence. R_s is a skill factor of operators and maintenance personnel. R_f relates to the adequacy of facilities, including workshops, special test equipment, and repair parts. R_d is a measure of the availability and quality of documentation, including operating and overhaul and maintenance manuals.

The basis for this reliability expression and the elements that influence it are shown pictorially in Figure 4. It is significant that product reliability is not a constant value but varies with the effects of these influences. The basis of this reliability expression will first be discussed in some detail and then related to impact upon unit production cost.



* LET - Limited Environmental Testing

FIG. 4 - BREAKDOWN OF RELIABILITY EQUATION FOR COST TRADE-OFFS

DESIGN RELIABILITY FACTOR, $MTBF_p$ (R_g): The prediction models as presented in MIL-HDBK-217 are developed from actual field failure rate experience and therefore, are the logical reference for estimating the potential reliability of any given equipment. It has been shown in numerous studies that individual products can exhibit widely different results when compared to such a prediction, depending primarily upon the maturity of the design, the effectiveness of the manufacturing quality control, and upon operational influences.

General Electric has published studies showing that reliability demonstration of radically new designs will typically realize approximately 10 percent of the MIL-HDBK-217 prediction value initially, improving to near 100 percent according to a growth

curve of variable slope determined by the effectiveness of reliability engineering during the design phase. Accordingly, the first two factors of the reliability equation, $MTBF_p$ and R_g, account for the influence of design and development engineering.

To predict the reliability ($MTBF_p$) of a given equipment configuration, the component parts are identified along with the design guidelines for environmental and electrical stress. The variables are:

- The quality of parts chosen, such as established reliability (ER) level L, M, P, R, S, or T for passive devices; JAN, JANTX, or JANTXV for discrete semiconductors; and MIL-M-38510, class C, B, or A for integrated circuits. A typical example would contain a mixture of parts and, for conceptual design, may have to be grossly estimated as provided for in the procedure of Section 3 in MIL-HDBK-217.

- The ratio of applied electrical stress to the device maximum rating.

- The environmental exposure limits of temperature, vibration, etc.

With these variables specified, an $MTBF_p$ can be determined. To realize the potential of this prediction, a test-analyze-fix program is essential for debugging new designs. It generally requires repeated cycles of operation under all combinations of environmental stress, with positive corrective action to remove design defects.

R_g is related to the intensity and duration of the test-analyze-fix program according to the graph shown in Figure 5. When a well disciplined reliability program is followed with quick reaction to test problems, the slope of the curve can be expected to approximate the straight line, a = 0.5 as plotted on log graph paper. The development of this relationship is covered in detail in "A Learning Curve Approach to Reliability Modelling", J. T. Duane, IEEE Transactions, Aerospace, Vol 2, 1964. When combined into an integrated test program (not dedicated to reliability growth testing) or with less than top priority given to failure analysis and corrective action design, the growth rate can be expected to follow the slope of a = 0.25 or less. Evaluation of trade-offs requires a judgement as to the appropriate value of a.

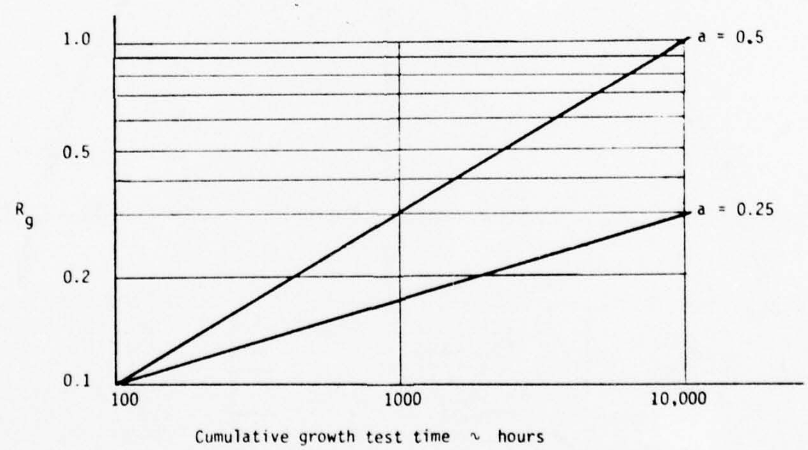


FIG. 5 - RELIABILITY GROWTH FACTOR, R_g, versus Cumulative GROWTH TESTING HOURS

<u>MANUFACTURING INFLUENCE FACTOR</u>, R_m: In theory, it does not matter that numerous defects are introduced into electronic equipment during the manufacturing process, so long as they are detected and corrected prior to final delivery of the product. This position will be examined in much more detail in a later discussion of cost consequences, but for the moment it is submitted that for reliability achievement, it is sufficient to employ limited environmental testing (LET) to remove (or confirm the absence of) manufacturing defects (material and workmanship). The more rigorous this test, within design limits, and the more cycles of exposure, the greater the probability that all manufacturing defects have been removed.

Figure 6 is a graphical representation of the empirically derived equation for removal of infant mortality failures in electronic equipment by use of repeated variation of environmental stress:

$$R_m = 1 - (1 - E_c)^n$$

where

E_c is a measure of the severity of the test environments relative to the design limits

n is the number of cycles of environmental exposure.

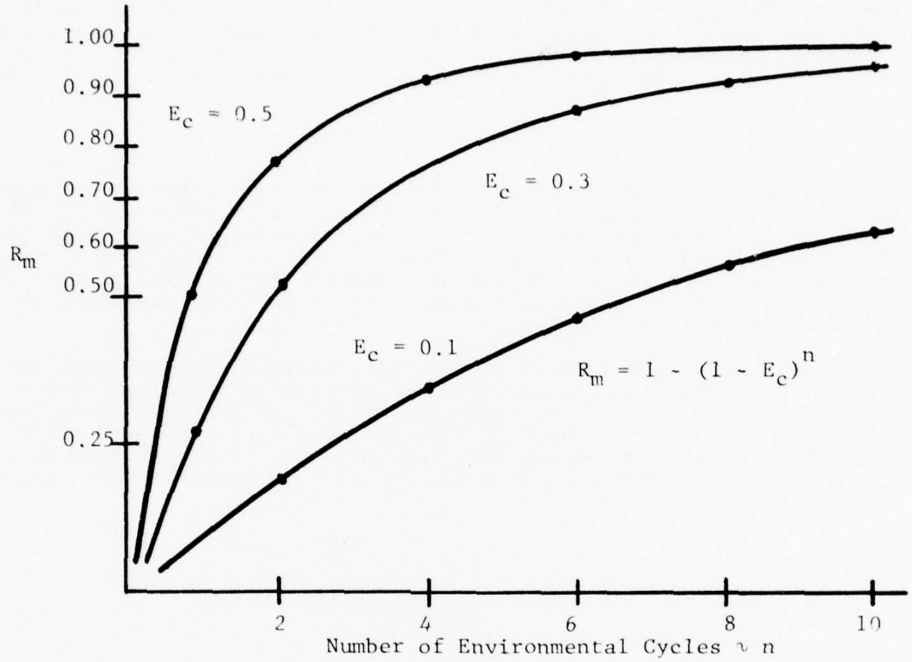


FIG. 6 - LIMITED ENVIRONMENTAL TESTING IMPACT

This expression is verified by data from an extensive study by R. W. Burrows in which results of environmental screening practices of 26 electronic equipment manufacturers were summarized. The curves for three representative values of E_c are shown. One is for the case of combined exposure to the two most critical environmental elements, such as temperature cycling and random vibration, with levels equal to the design limits, $E_c = 0.5$. Another curve, $E_c = 0.3$, is representative of temperature excursions of 50°C and sinusoidal vibration at 2.2g. The third curve shown, for $E_c = 0.1$, represents a burn-in screen where temperature is not cycled. To apply the equation, eight hours of burn-in is equivalent to one cycle i.e., for a 48-hour burn-in, n = 6. For test profiles that do not approximate either of these cases, a value of E_c may be estimated by considering the relative severity of the intended test to those described above, keeping in mind that $E_c = 0.5$ is probably an upper limit for any practical application.

OPERATION AND SUPPORT FACTOR, $R_s + R_f + R_d$: The final factor, $R_s + R_f + R_d$, is included in the model for completeness in accounting for total life cycle reliability. It has a negligible impact upon unit production cost and therefore, will not be expanded upon further. For quantitative reliability predictions, this factor will approach unity as field training and familiarity with the equipment increases. A judgement can be made of the appropriate value for each analysis based upon comparison to current or recent experience with equipments of similar complexity and application in a given operational organization.

COST CONSIDERATIONS: A general expression for the unit production cost of an electronic assembly is:

$$UPC = (M (1 + O_m) + L (1 + O_1)) (1 + G\&A) (1 + fee)$$

where

UPC = unit production cost

M = direct material cost

O_m = material burden rate, if applicable

L = direct labor

0_l = labor burden rate

G&A = general and administrative burden rate

Fee = profit fee rate.

M and L are the variables that may be impacted by reliability considerations $MTBF_p$ and R_m as shown qualitatively in Figure 2.

MTBF$_p$ COST IMPACT: To determine $MTBF_p$, it is necessary to specify the quantity and quality of component parts, including any requirement for supplemental screening/testing. If complete material lists exist for all design configurations that are to be considered for trade-off study, conventional cost estimating techniques are used to estimate the cost impact of each design.

For conceptual design, where detailed parts and materials lists do not exist for all design options, $MTBF_p$ is estimated by following the Section 3 method of MIL-HDBK-217, and the related material cost may be estimated from the relationships shown in Figure 7. Data was collected from several projects to compile Figure 7, which shows considerable variation and even some overlap in relative cost between the quality of part levels. Note that many different types of parts are represented and that judgement is required to select the most appropriate values.

In general, more exotic and complex parts will require a greater differential in price when quality requirements are increased. Conversely, common and simple parts can be tested extensively with relatively simple automation, resulting in very little increase in price. Set up charges, which must be prorated over each production lot, become quite significant when small quantities are involved. These factors were reflected in the data, and should be considered in using Figure 7 to estimate parts costs.

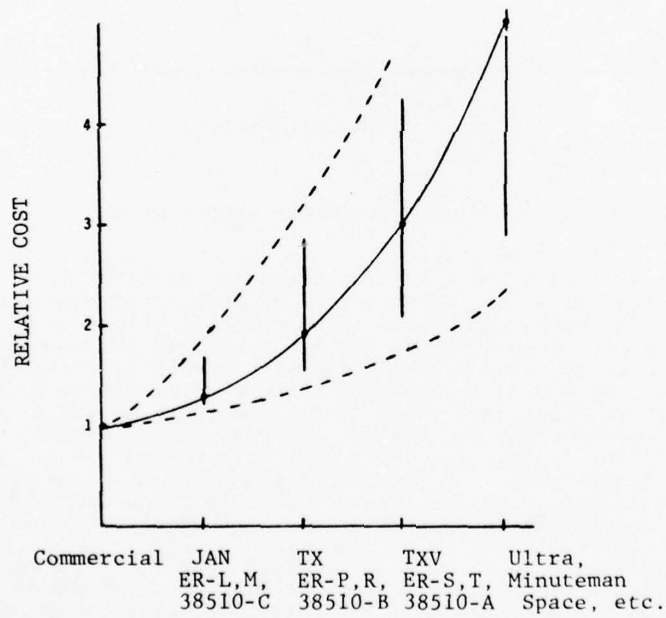


FIG. 7 - COST OF PURCHASED PARTS VERSUS SPECIFIED QUALITY

MANUFACTURING COST IMPACT OF RELIABILITY: The cost impact of R_m (manufacturing influence upon reliability) is much more complex. Selection of a value of R_m for the reliability equation implies that a finished assembly, after completion of LET will have a corresponding freedom from manufacturing defects. There may have been many failures, subsequent repairs, retesting, or none. Only the end result is significant for reliability achievement.

However, the means of realizing the failure-free finished product may be very significant to the costs incurred. Generally, there are three philosophies for setting up the manufacturing operation:

1. Carefully control each step in the manufacturing process so that no defects are introduced. This is the preventive approach and incurs cost for careful analysis and planning of all manufacturing operations. If successful, few if any failures will occur during LET and little or no cost is incurred in troubleshooting, repair, and retest.

2. Somewhat the opposite of the above is to build up all assemblies with minimal control and plan on multiple repetitions of the LET to remove the numerous defects until subsequent test cycles demonstrate the unit to be failure free.

3. The other philosophy is to study the economics of the application of the first two approaches and choose to emphasize one or the other on an individual manufacturing operation basis.

Approach number 1 must be followed where the cost of a specific failure is extremely high, for instance, when human lives may be threatened. It is generally the preferred approach for very complex equipment that is in high volume production. Number 2 is most attractive for very low volume production or for relatively simple assemblies where troubleshooting and repair are very easily accomplished.

Most electronics manufacturing companies who deal with government contracts set up their manufacturing systems to facilitate both high volume and low volume production. Thus, in most practical situations, approach number 3 is selected.

In general, manufacturing defects are avoided by careful adherence to detailed written instructions for each operation that have been thoroughly tested and proven to be effective. Such validated instructions apply to all manufacturing operations including procurement of material, in-house material handling, all fabrication and assembly tasks, inspection, test and package for shipment. Equal attention is required for housekeeping activities such as maintenance and calibration of test equipment, tools, gauges and measurement standards; personnel training and proficiency monitoring; and vendor selection, surveillance, rating, and control. To ensure that these instructions and controls are effective, a positive acting closed loop failure analysis and corrective action system is required.

For detailed analysis, direct labor, L, is subdivided into four categories:

$$L = L_{assy} + L_{test} + L_{sup} + L_{LET}$$

where

L_{assy} = all fabrication, assembly, and rework labor,

L_{test} = all in-line test, inspection, and troubleshooting

L_{sup} = all quality assurance and production engineering including failure analysis and followup

L_{LET} = LET labor.

Emphasis upon preparation and maintenance of instruction sheets, along with failure analysis and corrective action generally requires an increase in support labor, L_{sup}, and results in less troubleshooting labor, L_{test}, and less rework labor, L_{assy}. This suggests a subset trade study to find the minimum labor cost to achieve the reliability level (freedom from manufacturing induced defects) implied by R_m. An example that illustrates these cost interactions is included in a later section.

One manufacturing control element that is very important to the efficient production of modern avionics equipment is the incoming inspection of electronic parts. When a defective part must be detected and replaced after assembly onto a printed wiring board, it is commonly estimated that the cost is 10 times that of detection at the incoming inspection point. Further, if the printed wiring board containing a defective component part is installed into a higher assembly, the cost estimate for detection and repair increases to a factor between 30 and 100.

The cost impact of incoming inspection effectiveness is vividly illustrated by Table 11 from a recent study on the detection of integrated circuit defects. Data was recorded for the distribution of detected failures per thousand ICs tested at various assembly levels and for three separate incoming inspection methods. One method was to inspect a sample of 30 percent of parts received; a second method was to conduct 100 percent functional tests, and the third was to combine 100 percent environmental screening in addition to 100 percent functional tests. Using the first method, 30 percent sample testing, 3.2 defects per thousand devices were detected at incoming at an average cost per defect of \$0.50, 14.5 defects per thousand devices at the board level at a cost of \$10 each, 3.2 defects at the system level at an average cost of \$30 per defect, and 1.4 were detected in the field at a cost of \$100 per defect. The detection cost per

defect was proportionately higher for the other incoming inspection methods, $1 per defect for method two, and $6 each for method three, but the overall cost of removing integrated circuit defects from a system was $180 less for method two and $200 less for method three.

TABLE 11
DATA SUMMARY

Type of Incoming Inspection	Failures per 1000 Tested			
	Incoming	Board $ 10	System $ 30	Field $ 100
30 percent of devices tested	3.2 @ $0.50	14.5	3.2	1.4
100 percent of devices tested	15 $1.00	4.6	2.3	0.7
100 percent tested plus screening	21 @ $6.00	2.3	0.5	0.16

Figure 8 shows cumulative cost per system for the three methods. Another recent study suggests that in the general case the cost per defect at the system level and in the field could be much higher, which makes the effectiveness of incoming inspection even more significant than this example indicates.

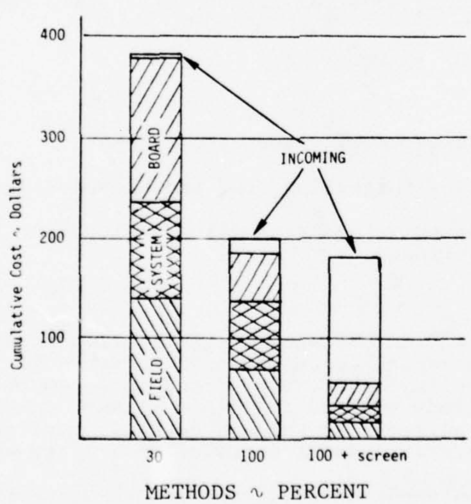


FIG. 8 - CUMULATIVE COST TO REMOVE INTEGRATED CIRCUIT DEFECTS VERSUS INCOMING TEST METHODS

The cost of conducting incoming inspection is frequently accumulated as a material handling overhead, designated as O_m in the UPC equation. For trade-offs involving the degree of incoming inspection, this factor should be adjusted accordingly. The procedure is to estimate the differential cost of the inspection alternative and to add (or subtract) from the standard cost (usual or baseline method of inspection). For the previous example, the differential cost of adding 100 percent screening is $6 per defect times 21 defects, less $1 per defect times 15 defects for each 100 devices tested. If the material cost, M, is assumed to be $2000 per 1000 devices, then an increase in material burden rate can be computed by dividing the added test expense by the material cost.

$$\Delta 0_m = \frac{\text{new test cost - old test cost}}{\text{total material cost}}$$

$$= \frac{(6)\ (21)\ -\ (1)\ (15)}{M} = \frac{126\ -\ 15}{2000} = 0.056 \text{ or } 5.6 \text{ percent}$$

If the standard inspection method is to conduct 100 percent functional testing without screening, at a 15 percent total material handling burden rate, then a burden rate of 20.6 is used for any trade-off alternative in which 100 percent screening at incoming inspection is chosen. Those companies who do not establish separate material burden rates may evaluate UPC trade-offs by setting $0_m = \Delta 0_m$, as calculated above, for any deviation from the standard incoming inspection method.

LET COST: The cost of environmental testing (LET) takes the form of a fixed setup cost plus incremental costs dependent upon the duration of the test. From the reliability considerations, the value (or set of values) of R_m dictates the number of test cycles to be conducted. The LET cost therefore may be represented by the equation:

$$L_{LET} = L_{cyc}\ (n) + L_s$$

where

L_{LET} = cost of conducting a specific LET

L_{cyc} = cost of one cycle of LET exclusive of setup

n = number of test cycles corresponding to R_m

L_s = setup costs

Graphical interpretation is provided in Figure 9. L_{cyc} and L_s are both directly proportional to the complexity of the unit under test, to the number of measurement points to be monitored, and to the length of time required to traverse one cycle, and inversely proportional to the amount of automation employed.

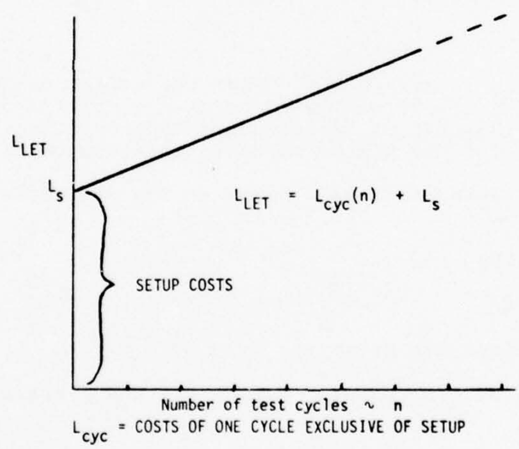


FIG. 9 - LIMITED ENVIRONMENTAL TESTING COST MODEL

The cost estimating procedure is:

1. Given the specific test requirements, obtain an estimate of the setup costs.
2. Obtain an estimate of the cost of one test cycle.
3. Determine the number of cycles required by the value of the R_m.
4. Calculate L_{LET}.

<u>EVALUATING TRADE-OFFS</u>: From the reliability equation,

$$R = MTBF_p\ (R_g)\ (R_m)\ (R_s + R_f + R_d)$$

it has been shown that variations in $MTBF_p$ and R_m alter unit production cost. From the UPC equation,

$$UPC = (M\ (1 + 0_m) + L\ (1 + 0_1))\ (1 + G\&A\ (1 + fee))$$

M, 0_m, and L vary with the reliability requirements. For evaluation of trade-offs, a matrix is suggested of R versus UPC as follows. If there are i alternatives of $MTBF_p$ and j alternatives of R_m, a UPC_{ij} can be calculated for each R_{ij} according to the relationships developed. After calculating all combinations, the trade-off evaluator has two alternatives; choose the least cost combination that produces an acceptable reliability, or choose the most reliability available at a given cost.

Example:

Given two choices each for $MTBF_p$ and R_m,

$MTBF_{p1}$ = 100 hours (use all JAN devices)

$MTBF_{p2}$ = 500 hours (all TX devices)

R_{m1} = 0.975 (six LET cycles, E_c = 0.5)

R_{m2} = 0.75 (two LET cycles, E_c = 0.5).

Since the factors R_g (for purpose of the example) and $R_s + R_f$ and R_d do not significantly affect UPC, they may be removed from the analysis by assuming them equal to 1.

Then

$$R_{11} = 100\ (1)\ (0.975)\ (1) = 97.5$$

$$R_{12} = 100\ (1)\ (0.75)\ (1) = 75$$

$$R_{21} = 500\ (1)\ (0.975)\ (1) = 487.5$$

$$R_{22} = 500\ (1)\ (0.75)\ (1) = 375.$$

The cost associated with $MTBF_{p1}$ is M_1 = \$2500. From the relationships shown in Figure 13 the cost associated with $MTBF_{p2}$ may be estimated as M_2 = (1.5) (\$2500) = \$3750. A judgement has been made here that the cost of TX devices is approximately one and one-half times the cost of JAN devices for the mix of parts in this equipment.

For both R_{m1} and R_{m2}, the LET setup time is 4 hours at \$8, and cycle labor is 4 hours each at \$7. Therefore,

$$L_{LET1} = \$28\ (6) + \$32 = \$200$$

$$L_{LET2} = \$28\ (2) + \$32 = \$88.$$

For R_{m1}, the following conditions are given:

Incoming inspection is 30 percent sample testing and the corresponding material burden rate is 11 percent.

L_{assy} is 60 hours at a direct labor rate of \$6.

L_{test} is 50 hours at a direct labor rate of \$8.

L_{sup} is 2 hours at a direct labor rate of \$10.

$$L_x = L_{assya} + L_{testa} + L_{supa} + L_{LET1}$$

$$= \$300 + \$400 + \$20 + \$200 = \$980$$

Therefore,

$$UPC_{11} = (M_1\ (1 + 0.11) + L_x\ (1 + 0_1))\ (1 + G\&A)\ (1 + fee).$$

Arbitrary values are assumed for 0_1, G&A, and fee since they are constant for all trade-offs.

0_1 = 1.5

G&A= 0.2

fee= 0.1.

Then

$$UPC_{11} = (\$2500(1.11) + \$980\ (2.5))\ (1.2)\ (1.1) = \$6897.$$

Substituting the cost of material associated with $MTBF_{p2}$,

$$UPC_{21} = (M_2\ (1 + 0.11) + L_x\ (1 + O_1))\ (1 + G\&A)\ (1 + fee)$$

$$= (\$3750\ (1.11) + \$980\ (2.5))\ (1.2)(1.1) = \$8728.$$

For R_{m2}, two situations are considered, and hence, two cost results for the same reliability result. The first situation is identical to R_{m1} except for the specified LET.

$$L_y = L_{assya} + L_{testa} + L_{supa} + L_{LET2}$$

$$= \$360 + \$400 + \$20 + \$88 = \$868$$

Therefore,

$$UPC_{12a} = (M_1\ (1 + 0.11) + L_y\ (1 + 1.5))\ (1 + 0.2)\ (1 + 0.1)$$

$$= (\$2500\ (1.11) + \$868\ (2.5))\ (1.2)\ (1.1) = \$6527$$

$$UPC_{22a} = (M_2\ (1.11) + L_y\ (2.5))\ (1.2)\ (1.1)$$

$$= (\$3750\ (1.11) + \$868\ (2.5))\ (1.2)\ (1.1) = \$8359.$$

The second situation for R_{m2} is with incoming inspection changed to 100 percent functional testing and a corresponding material burden rate of 13 percent. As a result, the breakdown of labor is

L_{assyb} = 40 hours at \$6

L_{testb} = 20 hours at \$8

L_{supb} = 10 hours at \$10.

The reduction in assembly and test labor is partially due to the more thorough incoming testing and partially due to increased quality support such as vendor surveillance and failure analysis.

The new labor total is given by

$$L_z = L_{assyb} + L_{testb} + L_{supb} + L_{LET2}$$

$$= \$240 + \$160 + \$100 + \$88 = \$588$$

and correspondingly

$$UPC_{12b} = (M_1\ (1.13) + L_z\ (2.5))\ (1.2)\ (1.1)$$

$$= (\$2500\ (1.13) + \$588\ (2.5))\ (1.2)\ (1.1) = \$5669$$

$$UPC_{22b} = (M_2\ (1.13) + L_z\ (2.5))\ (1.2)\ (1.1)$$

$$= (\$3750\ (1.13) + \$588\ (2.5))\ (1.2)\ (1.1) = \$7534.$$

<u>RANKED ORDER SUMMARY</u>

R_{21} = 487.5 hours	UPC_{21} = \$8728
R_{22a} = 375.0 hours	UPC_{22a} = \$8359
R_{22b} = 375.0 hours	UPC_{22b} = \$7534
R_{11} = 97.5 hours	UPC_{11} = \$6897
R_{12a} = 75.0 hours	UPC_{12a} = \$6527
R_{12b} = 75.0 hours	UPC_{12b} = \$5569

The results shown here are of no particular significance, because the values selected for the variables may or may not be representative. The intention of this example is to illustrate the application of the relationships developed to the reliability versus unit production cost trade-off analysis.

<u>TRADE-OFF MODEL TEST</u>: As a test of the validity of the reliability model, the data from a multiplex set is used as an example exercise. The data given for this equipment included the reliability mean time between failure prediction, some details of the reliability growth development program, and the results and conditions of production reli-

ability testing. As in the earlier example, the post deployment or logistics influence is normalized by setting the total $R_s + R_f + R_d$ equal to unity. Recalling the reliability equation

$$R = MTBF_p\ (R_g)\ (R_m)\ (R_s + R_f + R_d),$$

first, substitute the predicted mean time between failure of the multiplex set

$$MTBF_p = 4945 \text{ hours.}$$

Second, estimate R_g. Since a very comprehensive growth program of greater than 10,000 hours has been conducted, it may be assumed

$$R_g = 1.$$

Third, estimate R_m. When a burn-in screen without temperature cycling is used, the stress that induces failure where manufacturing defects exist is much less, and faults will be detected at a lesser rate. One cycle of a typical temperature cycling screen will take six to eight hours to complete. Therefore, in terms of exposure time only, 48 hours of burn-in equates to approximately six to eight cycles. Choosing $E_c = 0.1$ and $n = 6$, solve for R_m

$$R_m = 1 - (1 - E_c)^n = 1 - (1 - 0.1)^6 = 0.47$$

The resulting predicted reliability is then

$$R_1 = 4945\ (1)\ (0.47)\ (1) = 2324 \text{ hours.}$$

This compares favorably with the observed failure rate, calculated at the 60 percent confidence level, of 2716 hours.

A trade-off was considered where less expensive, lower quality parts would be substituted and more rigorous screening conducted on the completed assemblies. For this second configuration, all integrated circuits would be specified to requirements of MIL-M-38510, class C, and discrete semiconductors to JAN. The resulting reliability prediction in accordance with MIL-HDBK-217B was 2060 hours. The new screening requirement for completed assemblies included six cycles of temperature cycling from C to 50 degrees centigrade combined with 2.2g vibration at 60 Hertz. It was assumed that these variations would have no effect upon the results achieved by reliability development growth testing. The alternate reliability was

$$R_2 = 2060\ (1)\ (0.86)\ (1) = 1770 \text{ hours.}$$

The actual cost of the multiplex equipment gives a UPC_1 corresponding to R_1. Recent average production values are

Material, M_1 = \$7400

Labor, L_1 = \$3160

O_m = 0 (redistributed into labor burden)

O_1 = 150 percent

G&A = 20 percent

Fee = 10 percent

$UPC_1 = (M_1\ (1 + O_m) + L_1\ (1 + O_1))\ (1 + G\&A)\ (1 + fee)$

$= (\$7400 + \$3160\ (2.5))\ (1.2)\ (1.1) = \$20,196.$

The alternate cost, UPC_2 corresponding with R_2 is

M_2 = \$5300

L_2 = \$3760 (increased because of added setup time for screening and more test and repair due to lower quality parts, i.e., more defects detected)

$UPC_2 = (\$5300 + \$3760\ (2.5))\ (1.2)\ (1.1) = \$19,404.$

SUMMARY DATA

	Reliability	Cost
Alternate 1	2324 hours	\$20,196
Alternate 2	1770 hours	\$19,404

Alternate 2 was not selected because although it results in a four percent cost reduction, the reliability is reduced by almost 24 percent to a value that did not meet the requirement.

This example demonstrates the utility of the estimating relationships as well as showing excellent correlation between predictions and actual results observed.

OPERATION AND SUPPORT COST MODELS: An essential ingredient in an LCC model is the development of operation and support (O&S) cost models. These models are basically analytical in nature. That is, an operations, maintenance and support scenario is first developed, and around this scenario, a complete cost model is developed. Examples of relationships explored in the development of such models are: the quantitative effect of reliability on the number of maintenance actions and spare parts requirements; the effect of maintainability on the number of maintenance man-hours required, and the manpower required per maintenance action; and the development of materiel costs, and costs per man-hour, for the required maintenance activities. A virtual plethora of such models have been developed in the past; one report published almost eight years ago contained 46 different models ("Using Logistics Models in System Design and Early Planning", the Rand Corporation, Santa Monica, California, February 1971).

Operating and maintenance costs are the sum of initial and recurring costs over the system life cycle. The O&M cost model is therefore the summation of every significant cost element. For illustrative purposes, the following cost elements are extracted from the O&S modeling portion of a United States Department of Defense Publication, "Life Cycle Costing Guide for System Acquisitions", (Interim) January 1973. The guide lists the following as pertinent O&M cost factors:

1. Operational Personnel and Consumables Costs
   a. Personnel
   b. Consumables

2. Training Costs
   a. Initial and Replacement Training
   b. Recurring Training

3. Maintenance Costs
   a. Organizational
   b. Intermediate
   c. Depot (system level)
   d. Depot (subsystem or component level)

4. Facilities

5. Initial Government Materiel and Services

6. Support and Test Equipment

7. Data

8. Initial Spares and Repair Parts

9. Salvage and Disposal

10. Initial and Replacement Transportation

11. Supply Management

12. Development and Test

Equations provided for the first four items are:

1. Operational Personnel and Consumables Costs

   a. Personnel

$$COP = \sum_{k=1}^{Y} D_k \sum_{j=1}^{NT} \sum_{s=1}^{NS} (PR_{sjk}) (CP_{sj})$$

where:

COP = Life cycle operational personnel cost.

CP_{sj} = Average annual cost (including all pay, allowances, medical care, dental, retirement, etc.) of a man of skill "s" and type "j".

D_k = Discount factor for year "k" to generate a "present value".

NS = Number of combinations of different skills and levels within skills.

NT = Number of types of personnel

PR_{sjk} = Number of required personnel (including the Government provided factor to account for leave, sickness, etc.) of skill "s" and type "j" in year "k". (Wherever this symbol occurs, it refers to personnel relevant to that equation).

Y = System operating life cycle (to the nearest year).

j = Type of personnel (civilian/military/etc.)

k = Year in life cycle of the system.

s = Skill type and level.

Double counting of costs where operating personnel perform maintenance must be avoided.

b. Consumables

$$COC = \sum_{k=1}^{Y} D_k \sum_{i=1}^{NC} (RC_i)\ (CUC_i)\ (HC_{ik})$$

where:

COC = Life cycle operational consumables cost.

CUC_i = Cost of operational consumable item "i" per unit consumed, including cost of transportation to point of use.

HC_{ik} = Programmed operational use time (hours of utilization), in year "k" of the ships, aircraft, etc., which consume item "i".

NC = Number of consumable items.

RC_i = Consumption rate (units/hour of utilization) of consumable item "i". (Hours of utilization must be compatible with those in HC_{ik}.)

i = Item number ("i" will be used throughout this Guide to identify consumable and recoverable items).

Other symbols are as previously defined.

Items visualized under the operating consumables category are *POL, electrical power, hydraulic/pneumatic power, heating, and cooling energy, nuclear power, and consumable materials. Although the equation is generally applicable to each of these categories, it may require somewhat different inclusions within the specific terms. For example, POL consumption will consider cost per unit of consumption (pounds, gallons, etc.) times utilization hours. In the case of nuclear power, capital outlays may be required at specific dates (e.g., core replacement), and these will be discounted from their respective dates.

2. Training Costs

a. Initial and Repacement Training

$$CIT = \sum_{k=1}^{Y} D_k \sum_{j=1}^{NT} \sum_{s=1}^{NS} ((CI_{sj})\ (PR_{sjk} - PA_{sjk} - PF_{sjk}) + (CU_{sj})\ (PA_{sjk}))$$

where:

CIT = Total initial and replacement training cost of personnel.

CI_{sj} = Induction and initial training cost per man (entire cost, including pay and allowances, to bring a man into the service and up to the required skill type and level "s" for personnel type "j").

CU_{sj} = Update training cost per man to bring available personnel up to the required level for skill type and level "s" and personnel type "j".

PA_{sjk} = Number of available personnel of skill type and level "s" and personnel type "j" that do not require initial training in year "K" but do require update training.

PF_{sjk} = Number of personnel of skill type and level "s" and personnel type "j" that are available and fully trained in year "k".

Other symbols are as previously defined.

* POL is defined as power, oil, lubricants, etc.

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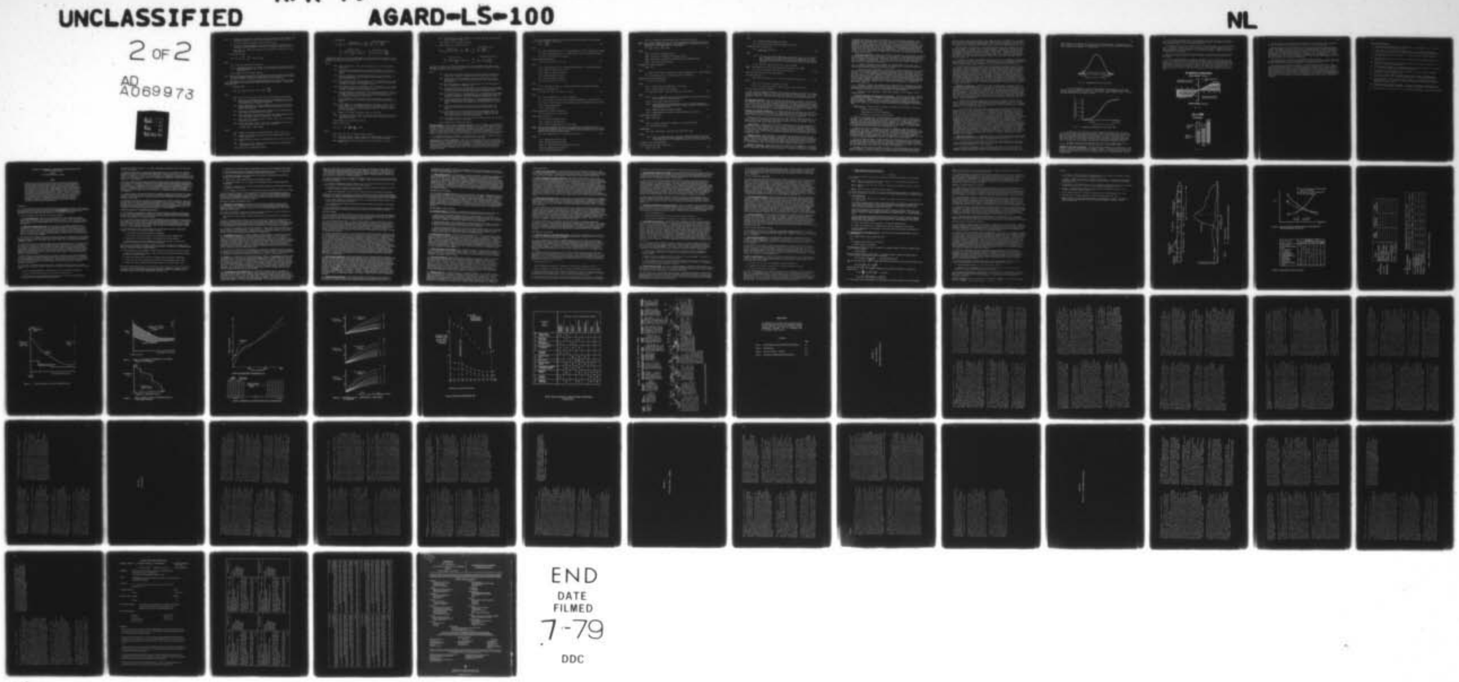

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Notes: 1. Personnel types and skill levels will include categories cited as operational personnel in equation 1a, and all other categories used in this system.

2. Also note carefully the definition of PA_{sjk} and PF_{sjk}.

3. Personnel must be available to work on the system under consideration (e.g., not merely available within the Service but assigned to another system).

4. PA_{sjk} and PF_{sjk} variations from year to year include a reflection of turnover rates.

b. Recurring Training

$$CRT = \sum_{k=1}^{Y} D_k \sum_{j=1}^{NT} \sum_{s=1}^{NS} (CR_{sjk}) (PF_{sjk})$$

where:

CRT = Life cycle recurring training cost.

CR_{sjk} = Recurring training cost in year "k" to maintain the proficiency of those personnel working on the system, for skill type and level "s" and personnel type "j".

Other symbols are as previously defined.

Note: The use of PF_{sjk} in the equation for recurring training is based on the premise that those personnel entering the system during year "k" would be fully trained and would not require recurrent training until the succeeding year.

3. Maintenance Costs: In the maintenance equations below, exclude labor costs for those tasks which are accomplished by operating personnel costed above. (Operational Personnel Costs).

a. Organizational

$$CMO = \sum_{k=1}^{Y} ((D_k) (HO) (CLO) + CCO + CRO)) \frac{(HUP_k)}{HT}$$

where:

CMO = Life cycle material and labor cost for organizational maintenance.

CCO = Total cost of consumable material used in organizational level maintenance during the operational test period. (Includes the cost of items identified as "discard-at-failure").

CLO = Average organizational level maintenance labor cost per man-hour to repair items which were removed during the operational test period (direct and indirect).

CRO = Total cost of recoverable material condemned at the organizational level during the operational test period.

HO = Total maintenance labor man-hours used in performing organizational level maintenance during the operational test period.

HT = Total utilization hours of ships, aircraft, tanks, etc., during the operational test period.

HUP_k = Total operational hours of utilization programmed for this entire force of aircraft, ships, tanks, etc., in year "k".

$$= 12 ((RUO) (NOU) + (RUT) (NTU))_k$$

where:

NOU = Number of individual operational aircraft, ships, tanks, etc.

NTU = Number of individual training and other nonoperational aircraft, ships, tanks, etc.

RUO = Operational utilization rate (hours/month) per aircraft, ship, tank etc.

RUT = Training and other nonoperational utilization rate (hours/Month) per aircraft, ship, tank, etc.

Other symbols are as previously defined.

b. Intermediate

$$CMI = \sum_{k=1}^{Y} D_k \overset{\text{Repair Costs}}{((HI)(CLI) + CCI))} \frac{HUP_k}{HT} + \sum_{i=1}^{NR} \overset{\text{Replenishment Costs*}}{CRI_i \left(\frac{HUP_k}{HT}\right)} +$$

$$\sum_{i=1}^{NR} \overset{\text{Pipeline Costs*}}{\frac{(CPI_i)(HSI_{i,k} - HSI_{i,k-1})}{HT}} + \sum_{i=1}^{NT} \overset{\text{Transportation Costs}}{(NTI_i)(CTI_i)\left(\frac{HUP_k}{HT}\right)}$$

*The sum of pipeline costs and replenishment costs (for intermediate and depot levels combined) for each item "i" in any year cannot be less than zero. If negative, replace all terms involved by zero for that item.

where:

CMI = Life cycle material, labor and transportation cost for intermediate maintenance.

CCI = Total cost of consumable material used in intermediate level maintenance to repair units which were removed during the operational test period.

CLI = Average intermediate level maintenance labor cost per man-hour to repair items which were removed during the operational test period (direct and indirect).

CPI_i = Unit acquisition cost of recoverable item "i" multiplied by the number of times that item was removed during the operational test period and ultimately repaired at the intermediate level.

CRI_i = Unit acquisition cost of recoverable item "i" multiplied by the number of times that item was removed during the operational test period and ultimately condemned at the intermediate level.

CTI_i = Average round trip transportation cost (including packaging, administration and scheduling from removal to reinstallation) per unit of item "i" removed during the test period and sent to intermediate level, and condemned or repaired at that level.

HI = Total maintenance labor man-hours used in performing intermediate level repair on the units that were removed during the operational test period.

$HSI_{i,k}$ = The number of total operating hours for the entire force of aircraft, ships, tanks, etc., programmed during the intermediate repair cycle time for item "i" in the year "k" (where cycle time covers the period of time from removal to reinstallation of item "i", based on first-in, first-out processing).

NR = Number of different recoverable items in the system.

NTI_i = The number of units of item "i" that were removed during the operational test period and sent to the intermediate level, and repaired or condemned at that level.

Other symbols are as previously defined.

c. Depot (System Level)

$$COD = \sum_{k=1}^{Y} 12\ (D_k) \frac{NOU}{MOD} + \frac{NTU}{MTD_k}\ (COH)$$

where:

COD = Life cycle cost of system overhaul at depot.

COH = Total cost (labor, overhead, round-trip transportation, and material) of individual aircraft, ships, tanks, etc., of each system overhaul.

MOD = Calendar months between overhauls of operational ships, aircraft, tanks, etc.

MTD = Calendar months between overhauls of training and other nonoperational *ships, aircraft, tanks, etc.*

Other symbols are as previously defined.

d. Depot (Subsystem or Component Level)

$$CMD = \overbrace{\sum_{k=1}^{Y} D_k \, ((HD)\,(CLD)) + CCD \, \frac{HUP_k}{HT}}^{\text{Repair Costs}} + \overbrace{\sum_{i=1}^{NR} CRD_i \left(\frac{HUP_k}{HT}\right)}^{\text{Replenishment Costs*}} +$$

$$\overbrace{\sum_{i=1}^{NR} \frac{(CPD_i)\,(HSD_{ik} - HSD_{i,\,k-1})}{HT}}^{\text{Pipeline Costs*}} + \overbrace{\sum_{i=1}^{NR} (NTD_i)\,(CTD_i)\left(\frac{HUP_k}{HT}\right)}^{\text{Transportation Costs*}}$$

*The sum of pipeline costs and replenishment costs (for intermediate and depot levels combined) for each item "i" in any year cannot be less than zero. If negative, replace all terms involved by zero for that item.

where:

CCD = Total cost of consumable material used in depot level maintenance to repair units which were removed during the operational test period.

CLD = Average depot level maintenance labor cost per man-hour to repair items which were removed during the operational test period (direct and indirect).

CMD = Life cycle material, labor and transportation cost for depot maintenance at subsystem or component level.

CPD_i = Unit acquisition cost of recoverable item "i" multiplied by the number of times that item was removed during the operational test period and ultimately repaired at the depot (subsystem or component level).

CRD_i = Unit acquisition cost of recoverable item "i" multiplied by the number of times that item was removed during the operational test period and ultimately condemned at the depot (subsystem or component level).

CTD_i = Average round trip transportation cost (including packaging, administration and scheduling, from removal to reinstallation) per unit of item "i" removed during the operational test period and sent to depot level.

HD = Total maintenance labor man-hours used in performing depot level repair on the units that were removed during the operational test period.

HSD_{ik} = The number of total system operating hours programmed during the depot repair cycle time for item "i" in year "k" (where cycle time covers the periods of time from removal to reinstallation of item "i", based on first-in, first-out processing).

NTD_i = The number of units of item "i" that were removed during the operational test period and sent to the depot.

Other symbols are as previously defined.

<u>THE SAVE PROGRAM</u>: A more recent development reported in the proceedings of the IEEE 1978 National Aerospace and Electronic Conference NAECON 78, Vol 3, is "System Avionics Value Estimation (SAVE)"; a new tool for Logistics and Support cost analysis. This is a collection of five special purpose computerized logistics and support cost models integrated within an interactive network. Developed by the Air Force Avionics Laboratory, it attempts to avoid problems of logical incompatibility, inconsistent input/output and a lack of overall guidance which arise when several different models are used in one procurement.

It is mentioned here as an example of the reduction of the myriad of O&M cost models to one computerized analytical aid. Its approach is worth emulating.

<u>RELIABILITY AS A CAPITAL INVESTMENT</u>: Life cycle cost modeling permits one to consider costed activities as investments, comparing the acquisition costs of any activity (investment) to potential savings in O&M costs (returns). One example of this is "Reliability as a Capital Investment" published in the proceedings of the 1974 Annual Reliability and Maintainability Symposium, Los Angeles, California. The following is the description given in the paper for computing the return on an investment in reliability activity during acquisition.

Return of investment (ROI) is simply the annual return divided by the investment cost. In the context of this paper:

$$ROI\ 1 = \frac{CO-CN}{CR} \qquad (1)$$

where:

CO = annual maintenance costs of a system procured without a reliability program.

CN = annual maintenance cost of a system procured with a reliability program.

CR = cost of the reliability program.

Further expanding the terms:

$$CO = V(1)\ V(2)\ V(3)\ V(4) \cdot 12 \cdot V(5) \qquad (2)$$

where:

V(1) = field failure rate of a system procured without a reliability program.

V(2) = number of parts in the system

V(3) = number of systems installed.

V(4) = operating hours per month.

V(5) = cost to repair a failure.

$$CN = V(6)\ V(2)\ V(3)\ V(4) \cdot 12 \cdot V(5) \qquad (3)$$

where:

V(6) = field failure rate of a system procured with a reliability program.

Remaining terms as defined above.

$$CR = (CM + CL + CT)\ (1 + V(26))\ (1 + V(27) \qquad (4)$$

where:

CM = cost of materials (i.e., parts screening)

CL = cost of labor for reliability activities excluding test related activity.

CT = costs of all reliability tests including labor and failure analysis activity.

V(26) = G&A overhead factor.

V(27) = profit factor.

Further expanding the terms of Equation 5:

$$CM = V(2)\ V(3)\ V(7)\ (1 + V(8))\ V(33) \qquad (5)$$

where (new terms only):

V(7) = cost of screening per part.

V(8) = materials overhead factor.

V(33) = ratio of semiconductors to total parts.

NOTE: This equation considers only the cost of semiconductor screens (i.e., microcircuits per MIL-STD-883 and other semiconductors per TX (specifications). Other populous high reliability parts (e.g., parts per ER specifications) are available without extra cost over standard parts.

$$CL = V(9)\ V(10)\ V(11)\ V(2) + V(12)\ V(13)\ V(14)\ V(2) \qquad (6)$$

where:

V(9) = engineering costs per hour.

V(10)= engineering overhead factor.

V(11)= no. reliability engineering hours per part.

V(12)= QC inspection costs per hour.

V(13)= factory overhead factor.

$V(14)$ = QC inspection man-hours/part due to reliability program.

NOTE: This equation computes the cost of routine reliability and QC inspection efforts caused by the reliability program. It is assumed that the amount of effort is proportioned to the complexity of the equipment.

$$CT = CABI + CRET + CRQT + CSBI \tag{7}$$

where:

CABI = costs due to assembly burn-in.

CRET = costs due to reliability evaluation testing.

CRQT = costs due to reliability qualification tests (demonstration).

CSBI = costs due to system burn-in.

Expanding the terms of Equation 7:

$$CABI = G \cdot H \tag{8}$$

when:

G = total hours of burn-in required for special assemblies (e.g., power supplies).

H = cost per hour for test technician and failure analysis.

Expanding the terms of Equation 8:

$$G = V(2)\ V(3)\ V(15)\ V(16) \tag{9}$$

where:

$V(15)$ = ratio of special assemblies to total parts.

$V(16)$ = length of burn-in per assembly.

$$H = V(32)\ V(17)\ V(13) + V(6)\ V(21)\ V(18)\ V(9)\ V(10)\ V(19) \tag{10}$$

where:

$V(32)$ = ratio of technical time to burn-in (assuming that continuous monitoring is not required for assembly burn-in).

$V(17)$ = cost of test technician per hour.

$V(21)$ = ratio of failure rate experienced in burn-in to field failure rate (also used as ratio of failure rate during reliability evaluation test to field failure rate).

$V(18)$ = number of parts per special assembly.

$V(19)$ = engineering hours needed for failure analysis per failure.

Returning now to Equation 7:

$$CRET = V(20)\ (AX) \tag{11}$$

where:

$V(20)$ = length of reliability evaluation test (operating hours)

AX = cost of RET per hour.

Expanding AX:

$$AX = V(17)\ V(13)\ V(34) + V(6)\ V(21)\ V(2)\ V(9)\ V(10)\ V(19)$$

where:

$V(34)$ = ratio of technician time to test hours assuming continuous monitoring and a test cycle including "equipment off" periods which do not count as operating time (i.e., countable test time is less than calendar time).

All other terms as defined above.

Continuing with the terms of Equation 7:

$$CRQT + (AA)\ (AB) \tag{12}$$

when:

AA = reliability demonstration test time.

AB = cost per hour for reliability demonstration test.

Expanding terms of Equation 13:

$$AA = \frac{1}{V(6)\ V(2)} V(22)\ V(23) \tag{13}$$

where:

V(22) = the ratio of specified MTBF (mean time between failure) to field MTBF. It is assumed the test specified MTBF will be higher than the field MTBF. No retest is assumed as the reliability evaluation test should have provided enough data to allow the specified MTBF to be met during the test.

V(23) = ratio of required test hours to specified MTBF.

NOTE: The remaining terms have been defined and provide the field MTBF.

$$AB = V(17)\ V(13)\ V(34) + V(6)\ V(9)\ V(10)\ V(19)\ V(2) \tag{13a}$$

Where all terms have been previously defined.

Concluding Equation 7:

$$CSBI = (V(3)\ V(24))(V(17)\ V(13) + V(9)\ V(10)\ V(19)\ V(6)\ V(25)\ V(2)) \tag{14}$$

where:

V(24) = hours of burn-in required per system.

V(25) = ratio of system burn-in failure rate to field failure rate.

All other terms previously defined.

Rate of return compares investment costs to annual recurring cost savings. Initial O&M cost savings are handled by subtracting these from the investment cost. For example, the paper shows that a reduction in the cost of initial spares procurement can be considered an immediate return and hence, subtracted from the cost of the reliability program.

LCC CONFIDENCE INTERVALS: Given the appropriate development, production, and operation and support costs for a system, one can then sum them to estimate total life cycle costs. It is obvious that, since each estimate is subject to some degree of inaccuracy or error, the total LCC will be sensitive, in different degrees, to some combination of the inherent errors. The following are extracts from an RADC study aimed at quantifying model sensitivity and developing procedures for estimating confidence intervals for LCC models. The work is still in progress and so is not available in the literature.

APPROACHES TO HANDLING UNCERTAINTY: The benefit derived from achieving cost visibility is greatly diminished if projections are frequently wrong and the costs portrayed are not representative of reality. As a result, methods must be used to account for the uncertainty involved and in this manner develop more credible projections of LCC.

Complete certainty can be obtained only from a historical perspective and this is too late to assist in the planning of the project at hand. However, various approaches to handling uncertainty are available and have been used at one time or another. Four of these approaches are briefly discussed below.

Safety Margins: Perhaps one of the oldest techniques for protecting oneself against uncertainty is to provide a margin of safety in the estimates of critical parameters. Quite often, the worst possible value of a parameter is used to represent the projected outcome. While this procedure can be used to establish an upper bound on possible costs, it can work to the disadvantage of a program by eliminating certain courses of action as too expensive when, in fact, they may be too expensive only if the worst possible set of circumstances occur.

Expected Values: Basing decisions on an expected outcome may well be one of the most common decision-making procedures in use today. The advantages of this approach is that it requires only a single estimate representing what the analyst feels will actually happen. Also, if the decision is made many times, the expected return will be realized. The disadvantage is that the degree of uncertainty that may affect the final decision is not reflected and it may not be possible to make the decision many times.

Sensitivity Analysis: Sensitivity analysis is another fairly common way of treating uncertainty. Use of this approach calls for one value, such as reliability, to be varied over its range while other values are held constant. This makes it possible to determine

the degree of sensitivity that a LCC estimate has to various input parameters. The technique works best when uncertainty exists about only a few parameters and when the parameters are independent (i.e., the effect on costs of the various parameters is separable). However, when uncertainty exists in a large number of input variables, the number of possible combinations of values becomes very large and may prohibit one from analyzing all possibilities. Also, the likelihood of some combinations occurring will be much less than the likelihood of other combinations. Straightforward sensitivity analysis will not reflect these changing probabilities and a LCC resulting from extreme values of all input parameters will appear just as likely as one resulting from the use of average input values.

Monte Carlo Simulation: Monte Carlo simulation provides yet another way of accounting for the uncertainties in input parameters of a LCC analysis. Such an approach requires that information concerning input variables be available to the LCC analysis model in the form of probability distributions. This means that either the raw input data must consist of probability distributions or else the model itself must convert deterministic input data into a probability distribution.

Likewise, the model output consists of a distribution of life cycle costs. From this output distribition it is possible to determine both the expected life cycle cost and the uncertainty associated with the estimate.

There are several advantages of a Monte Carlo simulation approach to LCC analysis over the more traditional sensitivity analysis approach. First, and perhaps most importantly, it provides information concerning the probability of occurrence of specific life cycle costs. LCC values arising from a sensitivity analysis are simply point estimates of a life cycle cost and nothing is formally given about the likelihood of any particular value occurring. Common sense tells us that the occurrence of extreme values in two or more parameters simultaneously is not as likely as the simultaneous occurrence of more moderate values. However, this difference in probability is not quantified during a normal sensitivity analysis where it can be when the analysis is conducted by Monte Carlo simulation.

Second, it relieves the analyst of the responsibility of deciding what combinations of parameter values to use in calculating a life cycle cost. Deciding which combinations of values warrant investigation and then making the proper calculations can be a burdensome task when there are a large number of input parameters.

Because of these advantages, a Monte Carlo approach to LCC analysis will be discussed further.

A Simulation Approach to Life Cycle Cost Analyses: There are several major considerations that should shape the development of any simulation model being designed for use in conducting a LCC analysis. First, it must be as accurate as possible. Next, it should be simple to operate and last, the output should be structured so that it is easy to understand. It is only by following these guidelines during model development that proper visibility can be given to the costs incurred by an equipment item over its life.

Model Accuracy: Model accuracy is largely a function of three things. These are

. Validity of the input data.

. Completeness of the cost categories.

. Treatment of the costs within the model.

Validity of the input data is in many respects an intangible that is difficult to quantify. It is dependent both on the ability of the analyst to extract and formulate the data as well as on the availability of data sources. As a result, the validity of input data can vary greatly from application to application. To accommodate this situation, data input requirements for a model should be as limited as possible while still enabling the model to meet its output objectives. This point is pursued further in the discussion on model completeness immediately below.

Insuring that the cost categories of a model are adequately complete requires a great deal of attention. The model must contain a sufficient number of categories to be complete and also provide sufficient detail for control and decision-making purposes when evaluating design trade-offs. At the same time, the number of categories must be restricted in order to retain simplicity. The exact structure of the cost categories should represent a balance between accuracy and simplicity. The ultimate model structure is therefore somewhat dependent on the use to be made of the model results.

The use of CERs introduces a unique problem when insuring that the cost categories of a model afford complete coverage. CERs are not always straightforward and the original cost data upon which the relationships are based may not be readily available for analysis and verification. This means that the use of CERs should be restricted to those that are thoroughly documented or that can be verified in some manner.

Treatment of costs within the model may consist of simply summing up costs in different categories. The main caution to be observed on this point during model development is to make sure that all relevant costs are included and that none are included

more than once. This is particularly true if CERs are used to estimate cost. As stated earlier, the model builder must know in detail what costs are covered by a specific CER. One should also be willing to judge whether or not the history represented by the old data points used to structure the CER will repeat itself in the application being analyzed.

One other topic that needs to be considered when discussing the treatment of costs within the model is the Monte Carlo sampling procedure. A Monte Carlo Procedure operates by taking samples of possible values of input variables and combining them as dictated by the logic internal to the model to produce a final result. The input variables on most models are independent which means that any value of one variable can be selected and combined with any value of another variable. This is not always the case when dealing with a cost model and requires special attention to insure that the model yields accurate results.

The problem of dealing with dependent input variables (i.e., dependent cost categories) can be solved in two ways. The first is to combine all cost into more highly aggregated groupings which are no longer dependent. This is not desirable if the model is to be used to evaluate design trade-offs because the necessary cost detail will be lost.

The second method involves modifying the normal sampling procedure used by a Monte Carlo model. The cost categories must first be ranked in a priority or precedence order. This order can change from sample to sample, but must remain constant during a single sampling operation. The model will then obtain sample values of all input variables in the order dictated by the priority listing. The first value obtained will be selected from the entire range permitted of that variable. However, from that point on each subsequent variable will be checked to determine if a dependence exists between it and the variable previously selected. If a dependency does exist, the potential range of the second variable will be restricted to reflect the dependency relationship. The type of restriction imposed is dynamic and will vary from sample to sample during the simulation run. Model complexity will be greatly reduced if the priority list can be structured so that each variable will have to be checked for dependency only against the one preceding it on the list.

Simplicity of Operation: Simplicity of model operation goes a long way toward establishing its eventual usefulness. A model that is too complex to operate will not be used enthusiastically and as a result, may fall into disuse. As far as an analyst is concerned, simplicity of operation is determined by the requirements imposed on structuring the input data. Care must be exercised in this regard when dealing with Monte Carlo simulation models. Traditional thinking says that better results will be obtained when more precisely structured input data are used. With Monte Carlo models this often means that input data must be structured in the form of a histogram or probability distribution. This is a severe requirement and one that can only be carried out with difficulty for typical life cycle cost data.

An alternative to this approach is to structure the model so that it fits a known probability distribution around some type of point estimate (or possibly around a point estimate along with an indication of the distribution variance). It is something close to this latter approach that is recommended here in order to achieve the required simplicity in structuring the input data.

It is felt that a limited choice on the exact form of the distribution to be used can be left to the analyst without introducing undue complications. The recommended forms are either the uniform (i.e., rectangular) or the triangular distribution. Either of these can be easily specified by indicating the mean and a range around the mean. This type of estimate eliminates the need to formulate a probability statement to describe every piece of input data. Data items known with complete certainty would be input as a single point with no range associated with them. The rectangular distribution would be used when it is felt that no information whatsoever is available about the magnitude of the estimated or future cost with respect to its estimated range. The triangular distribution lends itself to the situation where sufficient information is available so that one is at least able to say that the occurrence of a cost near the extreme end of the estimated range is less likely to occur than a value near the estimated expected value. It is logical that as the life cycle progresses through the conceptual, validation and development stages, the ability to refine cost estimates will increase. This should result in a general narrowing of the input cost ranges as well as a shift from rectangular distributions to triangular distributions. In addition, the emergence of primary cost drivers, possibly as the result of sensitivity analyses, will occur and emphasis can be placed on refining these estimates to a higher degree than the less important cost estimates.

Model Output Structure: As indicated earlier, the prime consideration in structuring the output is to make it easy to understand and thus give visibility to the costs (and the associated uncertainty incurred by an equipment item over its life.

A basic item of output required from the Monte Carlo analysis is a probability distribution describing the life cycle cost of an item. This could appear in tabular form or as shown graphically in Figure 10 below.

Once this is obtained, it is a relatively easy matter to give the degree of confidence associated with any particular interval estimate of life cycle cost. The example in Figure 10 shows that there is a 90% chance that the total life cycle cost of

some hypothetical system will be between $1,200,000 and $980,000. A program manager is now in a much better position to make decisions concerning program funding with uncertainties concerning cost exposed for consideration.

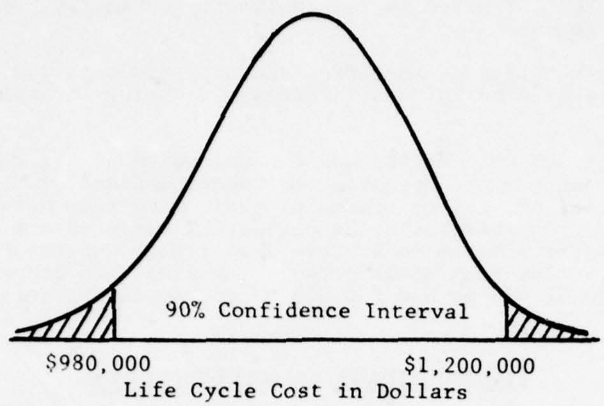

FIG. 10 - DISTRIBUTION OF LIFE CYCLE COST

It may be desirable to structure the probability distribution of life cycle cost in terms of a cumulative probability distribution. This information would then indicate the probability of a life cycle cost having a specific value or less. It could be shown graphically as in Figure 11 below.

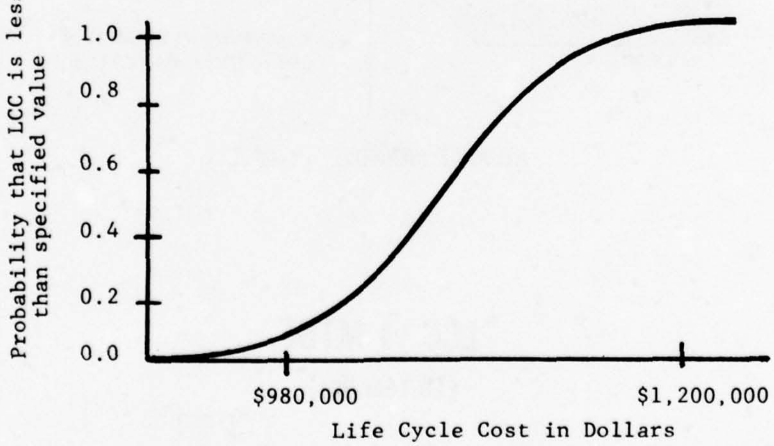

Fig. 11 - CUMULATIVE DISTRIBUTION OF LIFE CYCLE COST

In addition, it is felt that an option should be available where life cycle costs would be broken down into annual amounts. This would provide a cost profile that would further aid decision-making by giving visibility to the continuing as well as the peak year funding necessary to carry out a project. The penalty paid for the use of this option would be an increased requirement for data inputs. Cost data would either have to be input on a year-by-year basis or else an arbitrary allocation scheme would have to be exercised by the model to accomplish a year-by-year assignment of cost.

An option could also be provided so that costs could be shown either with or without the impact of inflation and the application of a 10% discount factor.

EXAMPLES OF LCC MODEL APPLICATION: The most prominent example of the application of life cycle cost models is the AN/ARC-164 Procurement Program. The program's objective was to produce a low life cycle cost radio to replace a variety of radios used by the Air Force, reducing annual maintenance costs and eliminating the costs of supporting more than one standard radio.

An LCC model was provided each of the competing contractors who were to use their fixed price production bid as the acquisition cost and estimate the O&M costs from Air Force equations similar to those presented previously.

The achieved LCC was to be verified by actual field measurements of the LCC parameters (e.g., reliability, repair costs, data costs, etc.) and an incentive/penalty of up to 25% of the contract price determined by the difference between the computer LCC based on field measurements and the LCC based on the contractor estimates. Figure 12 shows the incentive/penalty arrangement.

One other provision was that if the LCC based on field data was $\pm 3\%$ of the bid LCC no incentive or penalty would be invoked. This was to allow for some uncertainty in the results.

The most significant O&M cost driver was determined to be the reliability of the radio. The successful contractor, Magnavox, Ft Wayne, Indiana, made his own analysis of the cost vs the benefit of various values of radio mean time between failures (MTBF) summarized in Figure 13. On this basis, he bid on LCC based on a 1,000 hour MTBF. He then geared his reliability program to achieve that figure and the LCC field tests indicate he actually did better than anticipated. The final LCC computation from the field results was within 3% of the bid LCC and hence, no incentive/penalty was actually paid.

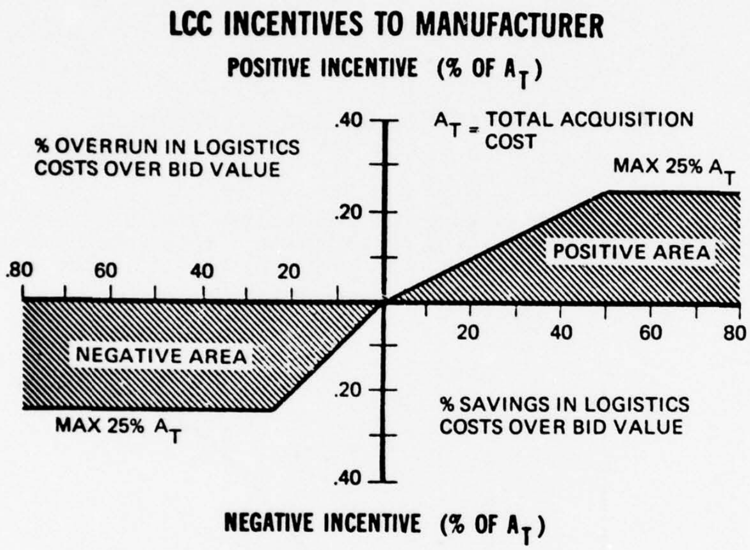

FIG. 12

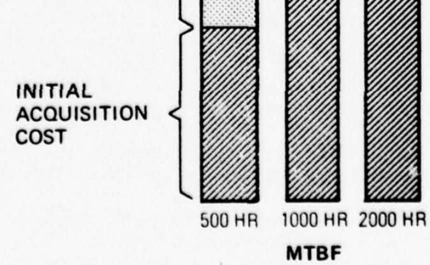

FIG. 13

This program thus provided a practical exercise of LCC modelling, and its apparent success in achieving its LCC goals will likely lead to more such exercises.

Another application of LCC modelling is in the use of Reliability Improvement Warranties (RIWs) where LCC modelling is used to determine whether a warranty arrangment is more cost effective than the normal situation of maintenance by the purchasing organization. The RIW requires the producer to make all repairs to his product for an extended period of time (normally 3-5 years) and hence, is an incentive for him to make all possible cost-effective improvements to reliability and maintainability. In applying the warranty, the cost of the warranty and its benefits are weighed against the cost of organic maintenance, through LCC modelling.

One application of a RIW was to the AN/ARN-118 TACAN procurement. A life cycle cost analysis determined that a four year warranty followed by organic maintenance would have a lower LCC than pure organic maintenance for a ten year life cycle.

The contractor also committed himself to an MTBF guarantee of 800 hours. This provision required the supply of additional spares to the Air Force if the field MTBF did not achieve 800 hours. The contractor hence had an incentive to achieve high reliability both to reduce repair costs for higher profit under the warranty fee, and to avoid the penalties of not meeting the MTBF guarantee. Latest field results indicate a MTBF of 1800 hours is being achieved. The success of this program will undoubtably spur the further use of warranties, and LCC modelling will be required in each application to weigh the life cycle costs of the warranty approach against those of the conventional approach.

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PROBLEMS IN THE INVESTIGATION OF RELIABILITY-ASSOCIATED LIFE-CYCLE COSTS OF MILITARY AIRBORNE SYSTEMS

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SUMMARY

Improved control of those life-cycle costs that are associated with reliability requires better understanding of how they arise, and of the relationships between the many possible sorts of investment in better reliability and maintainability and the benefits it achieves. Basic problems in deriving these relationships are discussed, with particular reference to overcoming difficulties of data acquisition, and to methodology for handling such complex properties as the "reliability" and "maintainability" of airborne weapons systems. Specific problems of Cost Analysis are discussed, including some novel aspects of "burn-in". The need is stressed for dealing with operational effectiveness on a par (and jointly) with cost estimating, if the results of the latter can be expected to have a significant influence on decision-making: some of the consequent problems of analysis are considered. In the conduct of projects, the importance is stressed of providing an adequate information system, to aid timely decisions on the trade-offs and investments associated with reliability and maintainability.

INTRODUCTION

1. It is first necessary to explain the term "reliability-associated life-cycle costs". This is taken here to include any cost incurred in achieving, improving and accommodating the properties of "reliability" and "maintainability" that are experienced in service. In what follows, these properties will be considered jointly (for reasons that will appear) and will be referred to as "R & M".

2. The costs discussed in this paper fall into two main categories:

a. R & M investment costs: these are the costs attributable to activities that are aimed at achieving or improving the reliability and maintainability of systems. Figure 1(a) depicts the phases during a life-cycle in which these activities can take place. It is to be noted that investment can continue after equipment enters service, in the form of modifications programmes aimed at improving R & M.

b. Support costs associated with R & M: these are the costs of maintenance attributable to "unreliability" and "unmaintainability" that is experienced during the service life of the system. Figure 1(b) illustrates the sort of cash flow associated with these. It rises sharply during the initial provisioning of spares, test-equipment and other supporting items, shortly before entry to service. After this point it may fluctuate considerably, for various reasons, but particularly as the amount of repair work or scheduled maintenance changes in response to initial learning processes and to R & M modifications programmes.

3. There seems to be considerable scope for controlling life-cycle costs through savings in these support costs, since they make an important contribution to overall expenditure. In Reference 1, for instance, a break-down of Royal Air Force Costs suggests that as much as 30% - 40% of the annual RAF budget might be attributable to them.

4. Authorities in life-cycle costing have, however, also stressed (References 2 and 3, for example) that the potential life-cycle costs of airborne weapons systems are largely determined in the extreme 'front end' of projects (ie before full-scale development has begun), particularly in the conceptual phase. I do not propose to challenge this, but would point out that provisions to meet requirements for enhanced 'performance' capabilities (in relation to those of earlier projects) can strongly influence the initial design options. They may therefore limit, to some extent, the control of life-cycle costs that can be exercised in the early phases, unless, as seems unlikely, large extensions to delivery time-scales are amongst the acceptable options.

5. Recent studies in the UK, sponsored jointly by the Royal Air Force and the Air System Controllerate of Ministry of Defence (Procurement Executive) have explored in detail the costs of R & M investments, and their relationships with life-cycle support costs. They have also been concerned with the influence of R & M investments on the operational effectiveness of aircraft fleets, and with the effects on dates of delivery to service that might result from additional R & M activities during project definition, development and production.

6. The question of 'operational effectiveness' will be discussed in more detail later, but, before proceeding, some clarification is needed. Expressions of operational effectiveness can take the following forms:

a. extent of training programmes, or other exercises, that can be undertaken in peacetime

b. potential flight-line availability in case of periods of tension or war

c. effectiveness, given full serviceability on the flight-line, that would be achieved during operational sorties in representative war-time scenarios.

Of course, a. is mainly an adjunct to c., in that it determines the potential fitness of air and ground crews for wartime roles.

7. Life-cycle support costs, and particularly those attributable to R & M, can obviously be varied in accordance with the level of operational effectiveness that is sought, or permitted. It is therefore necessary to establish some reference level of effectiveness, if comparisons of life cycle costs are to be useful. The influence of a. upon c. is not easy to quantify, and a convenient working assumption is to take the level of a. observed in recent practice to be adequate (ie to assume that c. would not be significantly greater if a. were increased).

8. If one is seeking the reliability that minimises life-cycle costs at some fixed level of operational effectiveness, then the familiar representation of the optimising process needs modifying along the lines shown in Figure 2. To the pair of curves (I and II in Figure 2) that are usually shown is added Curve III, to represent the cost of making good the loss of effectiveness that is due to unreliability. Means for this were considered in a paper given in Lecture Series No 47(Reference 4) and included, for example, such means as simply increasing the size of the aircraft fleet. It is seen that, when the 'operational effectiveness' factor is taken into account, the effect is to increase the estimate of the optimum level of reliability.

9. In recent studies, we have simplified matters by considering investment costs and benefits in relation to levels of investment cost, and of R & M, that are estimated from systematic observations of equipment already in service. The "benefit" is expressed in terms of both reduced support cost and increased operational effectiveness.

10. There are two ways in which the support costs associated with R & M may be controlled. The first is through changes in the inherent reliability and maintainability: the second is by changes to maintenance practices, so that the costs of dealing with given levels of R & M may be reduced. In the recent studies mentioned earlier, the main emphasis has been on the former. However, during the course of the studies some indications have been given of the scope for reducing costs by improving maintenance practices, to be compared with the potential savings from improving the R & M levels themselves.

STRATEGY FOR EXPLORATION OF INVESTMENT/RETURN RELATIONS

11. The prospects for drawing useful inferences from a purely statistical treatment of costs in past projects on airborne systems appear to be very poor. The R & M investments and returns are confounded with many other important factors (including the prevailing accountancy procedures, and the particular levels of system capability or technology demanded).

12. One is therefore forced to consider the detailed mechanisms by which investment in R & M activities has influenced, or could have influenced, support costs and operational effectiveness. To investigate all such mechanisms over a number of whole airborne weapons systems * would be an enormous task. It would also fail to exploit the observation that some of their sub-systems* lend themselves much more readily than others to such quantitative study, and that some contribute very much more than others to support costs or to loss of operational effectiveness.

13. The problem,then,is to make a suitable selection of sub-systems for detailed, "case-history", treatment. The criteria for selection are likely to include:

a. A well-recorded and intelligible programme of development

b. A well-recorded history of in-service "R & M" modifications and their implementation.

c. Technology that is sufficiently modern to be representative of future projects.

d. Accessible data on R & M levels experienced in service, and from which to estimate their influences on maintenance costs and operational effectiveness.

These are not as easily satisfied as might be imagined, a priori, and in practice the number of cases worth considering for detailed investigation may not be very large. The selection of sub-systems finally chosen for the recent UK Studies is shown in Figure 3.

14. Following selection of the sub-systems, a method of study for each one can be outlined as follows:

A. Collection of representative samples of data on defect rates, associated maintenance activities and unit costs of the activities.

B. Collection of samples of data from which to estimate losses of operational effectiveness.

C. Estimate the life costs of maintenance associated with identified generic types of cause.

D. Estimate the losses of operational effectiveness associated with generic types of cause.

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* The term 'airborne weapons system' is used to describe a whole aircraft and its payload. The term 'sub-system' is used to denote a functional portion of this whole. Examples of sub-system are air-conditioning, propulsion, nav-attack, communications transceiver, etc.

E. Highlight the most important causes of maintenance costs and of loss of operational effectiveness.

F. Conduct historical review of the project with particular reference to the cost and effectiveness of the R & M activities,and to other factors affecting in-service reliability.

G. Hypothesize (and assign costs to) additional R & M activities that might have been profitably applied at various stages of the project.

H. Estimate the R & M gains associated with these additional activities.

I. Translate these gains in R & M to savings in life maintenance costs and increased operational effectiveness.

J. Generalize the results of I to cover whole airborne weapon systems, and indicate potential returns on investment in future projects.

K. Give a paradigm for the conduct of R & M activities in future major projects, based on A to J above.

It is seen that steps A through I constitute a detailed "Case Study" of each sub-system, and that this involves a thorough investigation of the "background"; ie, to the initial operational requirements, time-scales, contractual arrangements, and revisions to specification; etc. Steps G through I concentrate on the potential for improvement (one measure of which is the achievable reduction in life-cycle costs) to guide the formulation of policies for future projects.

DIFFICULTIES OF DEALING QUANTITATIVELY WITH R & M

15. Complexity of R & M properties: The conduct of the Case Studies has served to remind us that "R & M" of modern airborne weapons systems (and of their constituent sub-systems) are in reality very complex properties. All definitions of R & M prove more or less unsatisfactory, either because their application is aimed at too restricted a field, or, if they are intended for general use, because their constituent terms are vague.

16. Consider, for instance, the definition of reliability given in Reference 5, which, as an attempt to describe the concept briefly, seems at least as good as any other:

> "The ability of an item to perform a required function under stated conditions for a stated period of time".

It is when one comes to quantify 'ability' and 'time', and to specify 'functions' (and what constitutes satisfactory functioning) and 'conditions' that the difficulties begin. Imagine, for instance, the multiplicity of functions of even one sub-system (eg an airborne interception radar or nav-attack equipment) and the enormous variety of event sequences that can be demanded by the operator within a time-segment, and it is soon appreciated that 'reliability' of a whole tactical aircraft is an extremely complex property.

17. The concept of maintainability also presents difficulties. Some attempts at definition address it in terms of the time, or of manpower needed, to repair defects. It becomes clear, however, in Case Studies of the type referred to above, that the cost, duration and frequency of scheduled maintenance should also be taken into account when defining quantitative measures of maintainability.

18. Inter-dependence of R & M: The scheduled maintenance implies policies for assigning fixed intervals for the replacement or refurbishment of certain components or sub-assemblies. It is then impossible to treat reliability and maintainability independently of one another. Indeed, rates of 'defects' or 'failures' are often controlled by means of these 'life-ing' policies, the most familiar examples perhaps being found in jet engine components. For some purposes, scheduled maintenance can be treated as the response to patterns of regularly occurring defects. Its effects on life support costs, for example, can sometimes be estimated in a similar manner to those of randomly occurring defects. Dealing with consequences to operational effectiveness, however, calls for a sharp distinction to be made between scheduled and unscheduled activities. Additional expenditure on scheduled maintenance activities, spares holdings etc can provide a means for achieving increased 'availability'.

19. R & M may also be considered to be interdependent in another sense. Engineering design that is aimed at reducing the cost or duration of individual maintenance activities (for example, by making sub-assemblies or components more easily accessible) can lead to higher rates of defects. Multiplicity of interconnections, in the interests of modularity, has sometimes been identified as a cause of loss or reliability.

20. Pitfalls: It is common practice to express reliability in terms of a mean interval (eg operating hours, flying hours, number of sorties, etc) between specified events (eg failures, defects, maintenance actions, replacements, etc). This tends to give the impression that reliability is simple to deal with, which may well be the case with, say, domestic television sets, in which both the usage and the forms of failure are well established and predictable. With airborne weapons systems, however, there can be enormous variety in the conditions prevailing during an "interval", and in the types of "events". The variations in the consequences of an "event" (as measured by repair cost, or loss of mission effectiveness, for example) can be very large. This is why "Reliability Growth Models" that deal in systematic trends in mean time between failures can be so misleading, since the residual types of failure may have disproportionately serious effects as compared with those that have been eliminated.

21. Slow emergence of R & M characteristics: It is important to recognize that, at the start of a major airborne weapons systems project, there can only be a vague notion of the more significant forms of unreliability that are going to reveal themselves during development and production, and, subsequently, in operational service. Which is to say that specifications of Mean Times Between Failures cannot serve as much more than a frame of reference in the initial phases of a project. Data that are potentially accessible during late development, particularly after flight-testing has commenced, can be used as inputs to cost/effectiveness studies so that the most worthwhile improvements to R & M become identified in a progressive

manner. The specification of R & M objectives during a project is essentially an iterative process. They become more realistic and closely defined as the project progresses. Although an overall MTBF, with a detailed breakdown between sub-systems should be assigned initially, the counting of "failures" and what is to contribute to accumulated "time" is negotiable in the light of experience. The main problem is to convert the flood of data that is released, or potentially available, during development, production and early service into a timely flow of feedback information.

22. These characteristics of the R & M properties of complex systems, rule out the more obvious approaches to studying the investment/return relationships. For example, it might have been supposed that the following method could be followed:

a. Establish the relationship between investments in R & M, and the changes thereby induced in rates of defects, rates of scheduled maintenance activities, repair times etc.

b. Independently of a. establish the effects that given changes in the rates of defects, etc. have, or would have, on support costs and force effectiveness.

c. Combine the relationships of a. and b. so as to derive the required cost/benefit relationships.

In practice, such a method is not feasible, for the basic reason that it is not until one has investigated the nature of the defects, scheduled maintenance actions etc, that one knows <u>how</u> to express usefully changes in their rates. Their nature is understandable only when both the following properties have been investigated:-

a. The ultimate influence of all observed types of defect, and scheduled maintenance actions etc. on support costs and operational effectiveness.

b. The mechanisms whereby changes in engineering practices can change the incidences of the observed kinds of defect, etc.

It is therefore apparent that an iterative approach is required, in which the appropriate classifications of alleged defects become increasingly evident as more is learned of their basic causes and effects.

OTHER BASIC PROBLEMS

23. Most of these basic problems are associated in some way with difficulties of acquiring the necessary data. To some extent they arise because the recording and processing of data suitable for R & M investment/return studies has not been a major pre-occupation of routine data systems. To this extent they can be overcome in future studies, but several fundamental problems will persist.

24. Before considering these further, it is well to remind ourselves of some of the main items of R & M-associated costs that have to be taken into account. These are set out in Figure 4, in which it should first be noted that the items of investment cost listed in Figure 4a represent a broad classification. In practice they have to be broken down further into numerous sub-divisions to correspond to the many forms that R & M enhancement activities can take. There are general problems in deriving development and production costs, and their availability is dependent on type of contract. Attribution to their R & M content is inherently difficult, because R & M activities tend to be embedded in the more general processes of development and production.

25. Several points emerge from the matrix of R & M-associated support cost items shown in Figure 4b. The first is the complexity of the process of estimating these costs, particularly when one recalls the variety of unscheduled maintenance actions (eg to deal with many types of genuine defects, of alleged defects that are not confirmed, and of accidental damage not attributable to unreliability, etc). The second point is that it would be very remarkable if routine data systems were to provide directly the entries to elements of the matrix, for a particular type of aircraft: and even more remarkable if these were directly available for sub-systems of the particular type of aircraft. It is found in practice that the processes of estimating these entries are speculative and to some extent, arbitrary, largely because of problems of attribution. One has to proceed through indirect measures of cost, such as the manning levels or manhours attributed to particular sub-systems. Moreover, it is necessary to take into account items of 'fixed outlay' (in addition to running costs) that commit expenditure even before systems have entered service. The further process of associating support costs with particular kinds of defects or scheduled maintenance activities, (and hence to specific deficiencies of R & M for given sub-systems, is therefore one of gross approximation. The process is, however, well worth attempting, because useful assessment of cost/benefit ratios can be made even though the estimates of the R & M-associated support costs are no better than a binary order of approximation.

26. <u>Multifunctional Organisations</u> Several large organisations serve as sources of data for the above estimates, involving manufacturers and procurement agencies, as well as the operators of the weapons systems. Difficulties of attribution arise because these organisations are, of necessity, concerned with a wider range of functions than is implied by the acquisition, support and peacetime operation of the particular systems under study. Manufacturers, for instance, may be concerned with a much wider range of products, and their spare parts and repair facilities may serve a variety of customers, yet be subject to some common overhead costs. Maintenance personnel of the armed services are likely to have potential wartime roles (eg repair of battle damage) in addition to peacetime functions, and their manning levels are likely to reflect the several functions. For this reason alone, R & M investment/return studies must be based on estimates of the <u>marginal</u> effects of changes in investment and demand. Great care has to be taken when quoting unit costs, particularly with respect to defining the reference levels of cost/activity upon which they are based. The need is also implied to construct from past experience a picture of procurement and operation that can be periodically updated to take account of general trends within the organisations concerned.

27. <u>Operational effectiveness data.</u> Without going into detail at this stage, it should be pointed out that difficulties of data acquisition are by no means confined to those associated with costing. In particular, the estimation of loss of potential wartime effectiveness by aircraft fleets, due to R & M

shortcomings, makes demands for data that are extremely difficult to satisfy through routine peacetime procedures of data recording. The influences of defects on operational effectiveness are no less varied than their influences on support costs.

28. Basic sampling problem. It is inevitable, if recent (and, therefore, technologically representative) system acquisitions are to be studied, that samples of defect rates, and other rates of maintenance activities, are based on a relatively short segment of in-Service life (eg upon the first 3 years of a service life of 10-15 years). Variations of such rates throughout service life are illustrated in Figure 5. It is to be expected that, for any one sub-system, several plots of this kind would be required, each corresponding to one of the several kinds of "significant" defect or scheduled maintenance action that have emerged in service; (ie 'significant' with respect to support cost or to operational effectiveness). One cannot avoid speculative assumptions on future trends. One can ensure, however, that in comparing returns on R & M investment to be expected from different kinds of system, or sub-system, that the assumptions (eg on learning processes, on the ameliorative effects of modification programmes, and on 'ageing' processes) are reasonably consistent.

WARNING ON LIFE-COST MODELLING

29. The foregoing paragraphs are sufficient to alert the reader to the dangers of embarking, ab initio, on the construction of elaborate models of life-cycle costing. As in most areas of operational research, the models and their input data are in a 'chicken and egg' relationship. My advice is to take a look at the available sources of data and start with the simplest of models, then reconsider the forms of data that could be useful, and continue iteratively. It seems doubtful whether elaborate models would ever be justified in the study of R & M investment/return relations, in view of the basic assumptions that have to be made. I am inclined to extend this advice to all forecasts of total life-cycle cost of high performance airborne weapons systems, on the grounds that, to be valid, these must take account of operational effectiveness levels to be achieved during service life, and that the prediction of these will always remain imprecise.

SPECIFIC PROBLEMS OF DATA ACQUISITION

30. Incidence of defects. In addition to the inherent variations in defect rates during service life (para 28, above), three potential sources of gross errors of measurement have to be dealt with:

a. Defects of a sub-system may be wrongly attributed to other sub-systems of the aircraft. It is therefore important to define unambiguously the sub-systems under study and to ensure that the system of reporting is capable of associating identified defects with the parent sub-system, particularly when these occur in components of a type that is common to more than one sub-system.

b. The operational usage of the sub-system during the period sampled may be untypical. For avionics equipments, in particular, the use of Elapsed Time Indicators is helpful, and so also are means of collating routine stress measurements on the aircraft (eg from "g" meters).

c. Even with the above facilities, there is the risk of attributing flying hours of an aircraft fleet to sub-systems (particularly avionics) that have not in fact been carried, or operated, on all flights. It may be that the only way to guard against this, without imposing a tedious burden on routine maintenance reporting, is by a system of spot-checks at operational stations.

31. Assigning causes to defects. The most cost-effective improvements in R & M policies cannot be found unless the causes of defects from past projects can be identified. This is by no means as straightforward as might be thought, because the reporting of defects leaves much scope for interpretation. It seems to be common experience that a substantial proportion of defect reports is ultimately classified as 'no fault found'. Where a fault is confirmed, it may be attributable to mishandling rather than, say, to engineering design, or faulty workmanship. Close investigation of patterns of defects reported by the routine data system often leads to a changed diagnosis; for instance, through the highlighting of "epidemics" at centres of operation or maintenance, or of associations between defects and particular tail-numbers in the aircraft fleet. For many sub-systems (eg complex avionics and propulsion) participation by the respective manufacturers is essential to useful diagnosis.

32. Effect of burn-in on defect patterns. Since burn-in has become such a common practice, particularly for avionics sub-systems, it is of great interest to measure its effect on in-service defect patterns. There is a serious lack of relevant data from past projects. This can be remedied in future by controlled experiments that exploit in-service data, and collate them with the burn-in histories of sets of similar equipments, as described in para 49, below.

33. Spare parts consumption. Special provisions may be needed to determine the quantities of consumable spare parts used, for the sub-systems studied, during a given period of sampling. Difficulties are particularly likely where there are sorts of spares that are common to several types of aircraft or to several sub-systems on the same aircraft. In addition to these considerations, there is the question of 'end effects' if one is forced to use indirect measures of spares consumption; such as the quantities of spares of a given sort, that are ordered (or delivered) from time to time. In this case the length of sampling period should be sufficient to keep the quantization errors within acceptable limits. Some organisations, particularly the manufacturers of the sub-systems, may not have a standard practice of accounting separately for the spares, labour and overheads attributable to repairs and reconditioning, in which case further special provisions may be needed, for study purposes.

34. Manpower consumption. The same difficulties of attribution that apply to the measurement of spare parts consumption apply also to manpower consumption. Additionally, there is the problem of distinguishing between the manpower used on reliability - associated activities from that consumed by other duties of maintenance personnel (such as re-fuelling, flight-line aircraft handling, role-charge etc). The most direct means of estimating manpower is from the records of manhours attributed to particular tasks at the several lines of maintenance. It is desirable that these be checked by assessments of the manning levels associated with particular types of aircraft, with a breakdown, where possible, applicable to the sub-

systems being studied.

35. Quantities of rotable spares. It may not always be possible to distinguish the purchase of those equipments (or parts thereof) that are intended as the basic aircraft fit from those needed as 'pipe-line' stock to support repair cycles. The latter can be an important element of reliability-dependent cost, and, to estimate it in such cases, data are needed on effective sizes of front-line and reserve fleets.

36. Causes of consumption of spares and manpower. Mention has been made (paras 30 and 31) of the problems of counting and classifying defects. Even when these are overcome, special provisions may well be needed if the spares and manpower consumed in a given sampling period are to be attributed to particular types of defect and of scheduled maintenance actions. For maintenance within the operator's organisations, it has to be decided whether more detailed inputs to a centralized maintenance data system would be justified on a routine basis, or whether ad hoc methods of spot-sampling would be preferable. Repair and reconditioning work by manufacturers poses more difficult problems of attribution when sub-contractors are also involved. In addition to distinguishing between scheduled and unscheduled maintenance there may also be the problem of separating out work and materials expended on in-service modifications. Within the total quantities of spares and manpower consumed by the modifications programmes, data will be needed to distinguish the contribution to those modifications aimed at improving R & M, and to enable this to be attributable at sub-system level. Such data are likely to be more readily available for the avionics sub-systems than those parts of the aircraft that are commonly dealt with by 'blanket' provision of modifications funds.

37. Operational implications of R & M. The three aspects of operational effectiveness given in paragraph 6 suggest the kinds of data needed. Routine maintenance data systems may tend to overemphasise the effects of defects on peacetime training activities, at the expense of necessary detail on potential loss of wartime effectiveness. In view of the many possible wartime scenarios, even for a fleet of aircraft of the same type, collection of the latter sort of data could impose a heavy burden on maintenance staff, if undertaken on a routine basis.

38. For the implications of defects during the sorties in which they arise, a functional classification is needed, suitable for inputs to operational models of combat, support, strike or reconnaisance activities. At least, these should distinguish those defects that curtail the sortie, but it is also important to make finer distinctions in degrees of loss of effectiveness. For example, in the case of radar equipment for airborne interception, the incidences of losses of the various modes should be distinguishable in the data, and reductions in ranges of surveillance and missile control should also be recorded. It may well be that the collection of this sort of data would require special visits by analysts to operational stations, and, during these, exceptional contributions from air crews and maintenance personnel. These could be used to check, and to complement, the day-to-day system of data collection.

39. Flight-line availability at operational stations depends upon both scheduled and unscheduled maintenance activities. Commonly available data, such as the proportion of aircraft ready to fly at some stated time of day, are of limited value for application to wartime scenarios. They need to be supplemented with data on the degrees of unserviceability (giving causes) and, in particular, on recovery times. Data for the latter should be appropriate to assessing the effect of alternative assumptions on maintenance resources (stocks and manning levels) and on other features of battle conditions, such as damage and attrition.

SOME PROBLEMS OF COST ANALYSIS

40. Effects of changes in R & M on maintenance demand. The effects of improvements in R & M (eg those that could have been achieved with additional investments during development or production) will be to modify the shapes of the event-rate curves shown in Figure 5.

41. For each classified type of defect or scheduled maintenance action, new curves will be produced, reflecting decreases in the quantities of consumable spare parts,and in the labour required,for repairs or reconditioning. The difference between the areas under, respectively, the original and the new curves gives the reduction in the particular type of running (or on-going) demand on maintenance resources: this is illustrated in Figure 6. In practice, due to the difficulties enumerated earlier, one may have to settle for gross simplifications to these curves, using, for instance, estimates of life average rates (using only a very broad classification of types of defect) based on samples from a short segment of the life cycle.

42. Estimation the effects of improved R & M on the "fixed outlay" on rotable spares and on holdings of special test equipment,etc,present some difficult questions. To what extent, for example, can the improvements in R & M be predicted at the time at which decisions on initial provisioning have to be made? However, let us proceed on the assumption that this improvement can be predicted exactly. It would then seem reasonable to assume that the fixed outlay would vary in proportion to the maximum demand during the service life of the sub-system being studied:

$$\text{STOCK} \propto \max_t \left(F(t)\,A(t)\right);$$

where $F(T)$ represents the quantity of flying per unit calendar time during service life and

where $A(T)$ represents the number of defects or scheduled maintenance actions per unit flying time.

It is seen that knowledge of $F(T)$ depends on data, or assumptions, on the rate of build-up of the fleet, or of introduction of the equipment studied. (There are also such finer points as to whether the stock has any end-of-life value and whether some of it could be turned into consumable spares).

43. If the actual case history shows that the initial provisioning levels of rotables and test-equipment was unduly high, then it may necessary to postulate a rationalized procedure (applicable to provisioning

of these items in future projects) before applying the proportionality given in para 42.

44. Relating savings to reductions in demand. We have considered the estimation of potential reductions in demands on resources (spare parts, materials and manpower for repair and reconditioning), but not yet the ultimate savings in support costs. The difficulties in estimating the latter stem partly from the discontinuities (and other non-linearities) in 'overhead' costs, and partly from the multifunctional nature, discussed earlier, of organisations concerned with maintenance.

45. The direct costs of maintenance manpower (as indicated by wage rates, for instance) are small in comparison with the total costs that might be attributed to it, if existing budgetary estimates were allocated pro-rata to the sub-systems studied. They remain comparatively small even after the non-reliability-dependent element has been removed). The 'overheads' include supporting labour as well as the capital facilities. The studies of potential effects of additional investment in R & M enhancement suggest the possibility of substantial inroads (eg of the order of 50%) into the peacetime maintenance workload, in certain areas of technology. The potential inroads differ considerably for the respective areas of technology however, and it is not easy to arrive at a broad generalisation. However, some success has been achieved in particular areas, and Figure 7 illustrates the sort of relationship found in an example for which peacetime maintenance was the sole function of the organisation concerned. The discontinuities represent such discrete processes as the closure of whole buildings or other capital facilities.

46. A much more difficult problem arises when considering the scope for reducing manpower and its associated overheads at operational stations. One way of proceeding would be to express the potential benefit in terms of the extra effort that would be released for other activities (eg repair of battle damage) in wartime, and hence to convert to units of operational effectiveness rather than to those of support cost.

47. Allowing for differences in scales of procurement. The costs of investment and of support both depend upon the quantities of aircraft and equipment that are produced and operated. Comparison between the returns from investment in the R & M of the sub-systems studied require some kind of standardization of procurement scale, and a basis for reading them across to scales in future projects. Useful approximations can be made by dividing the costs into three classes, according to dependence on numbers produced and operated:

a. fixed (eg development costs)

b. semi-fixed (eg test-chamber facilities for quality control in production)

c. pro-rata (eg spares consumption in service, or in the repair of failures in burn-in)

48. Cost effectiveness of burn-in. Burn-in gives rise to reliability investment costs that comprise fixed, semi-fixed, and pro-rata elements. The pro-rata and semi-fixed costs tend to predominate and, no matter how large the production quantities, a substantial unit cost persists. For avionics, a typical order of burn-in cost per defect detected (in test-chambers), and rectified before delivery, is 1000 US dollars. Increasing the duration of burn-in tends to increase this unit cost, and to call into question whether a cost/effective basis has been established. Figure 8 shows the sort of functional relationship inferred in the case of an avionic equipment, for which sub-samples of the production run were burned-in for much longer than the average. A physical interpretation of this sigmoid shape is that the initial slope is predominantly due to the 'infant mortality' type of failure that burn-in is expressly aimed to eliminate. The rate subsequently settles down to a level suggested by the slope of the tangent to the point of inflection (Fig 8), which is independent of infant mortality and may be taken to have been constant up to this point; ie, to correspond to some underlying defect rate that is independent of infant mortality. Further time in the test chamber leads to the premature ageing suggested by the curve to the right of the point of inflection. The risk of proceeding too far beyond the point of diminishing returns is obvious.

49. In a thorough cost/benefit analysis of burn-in, it would first of all be necessary to estimate the extent to which the patterns of defects detected would have been reproduced in service (particularly, whether they would mostly arise early in service life). Steps to collect the necessary data to support such estimates have been suggested above. This done, and the consequent savings in-service repair costs estimated, the side-benefits of burn-in would also have to be taken into account. These include:

a. The provision of information on systematic defects, which can give a basis to programmes of reliability growth in production (It is important to distinguish this from the elimination of infant mortality).

b. Review of a means (for comparison with other methods, such as batch-sampling) of sustaining the contractor's attention throughout the production process.

c. Any side-benefits that arise from preventing 'bursts' of defects in early service. These might include the prevention of loss of morale, of excessive handling (hence of failures due to mishandling) and of hasty re-provisioning of maintenance resources.

50. Discounted cash flow (DCF): It is to be noted that investment to improve R & M can be made at any point in the life cycle, but that those made in the earlier phases may not reap their full benefit, in support cost savings, until some 20 years later. In a climate of high interest rates, the practice of discounting these savings can have a profound effect on investment/return ratios.

51. There does not seem to be a generally agreed rationale for applying DCF adjustments to defence project funding. It can be noted, however, that, with the patterns of reliability-associated cash flow that can be expected over the life of an aircraft project, and with an annual discount rate of 10%, an undiscounted return of between $1\frac{1}{2}$ to 1 and $2\frac{1}{2}$ to 1 would be required to break even (in a commercial sense) on investment made throughout the development and production phases.

52. It is also to be observed that, in the application of DCF, it might be possible to treat investment in burn-in as a special case, with considerable simplification. If the main benefit of burn-in is in fact,to eliminate defects in early service, then one would expect to reap it only a short while after the corresponding investment occurs on the production line. In this case, the effect of discounting might be negligible.

ANALYSIS OF OPERATIONAL EFFECTIVENESS

53. We touch now on one of the most difficult subjects related to the control of life cycle costs: the analysis of operational effectiveness (paragraphs 6-8 above). The particular aspect of concern in this paper is the loss of effectiveness due to unreliability and unmaintainability, and the potential for reducing this loss by improving R&M. In the comparison, between sub-system, of the potential returns they offer on R & M investment, the two forms of benefit (viz: reduced support cost and increased operational effectiveness) can suggest very different priorities if considered in isolation from one another. Estimates of both are essential to sound decision-making. For instance, a recent cost/benefit study of a proposed reliability-improvement programme, for an avionics equipment already in service, showed a poor return in the form of support cost savings. This was because much of the life support cost had already been committed to the provision of rotable spares and special test equipment. There was sufficient fleet life remaining, however, for the expected gain in operational effectiveness (equivalent to adding several aircraft to the fleet) to be the more significant consideration.

54. Need for high-level measures. The measures of operational effectiveness should lend themselves to selection of priorities (between sub-system investments) and to being weighed alongside predictions of support cost savings. This implies taking into account the role for which the whole airborne weapons system has been procured. There are usually several alternative ways (in addition to improving R & M) of off-setting a loss in the operational effectiveness of an aircraft fleet, and, ideally, one should compare them all. In practice, there is seldom sufficient data for this ideal procedure, but at least a useful upper-limit estimate can often be made of the value of the effectiveness gain, by translating it into an equivalent change in the number of aircraft of the fleet, and hence to a life-cost change. In Reference 4, Baker has considered the alternatives of fleet expansion and more intensive flying at constant fleet size. His arguments suggest that of the two alternatives, the cost of the former is likely to give the more valid measure, and that, in any case, their costs will not differ greatly unless there has been a substantial departure from the optimum allocation to aircraft, men, and other resources.

55. Operational modelling. This will usually require models of the operation of the airborne weapons systems in their wartime roles. In many cases, the estimation of high-level measures of changes in potential wartime effectiveness will be hampered by shortage of input data (as discussed earlier). Represenataion of the effects of battle damage to aircraft and airfields, and of supplies of maintenance resources, for instance, will be subject to many speculative assumptions. Elaborate, general purpose modelling does not seem appropriate to this field. The data that are readily available from peacetime operations justify only the most rudimentary models initially. These should be used in sensitivity analyses to indicate the sorts of information that will be needed from special processes of data collection at operational stations.

EXAMPLE OF WARTIME EFFECTIVENESS MODELLING

56. The example that follows is in illustration of the initial modelling needed for a given type of airborne weapons system, in order to investigate sensitivities to parametric values and to the assumptions used. It represents the sort of model that can be suggested by a quick look at those data that are readily available in peacetime.

57. Tactical airforce operations. The airborne weapons system chosen as an example consists of an aircraft and payload designed for the close-support role in land battles. We make use of the basic assumption, suggested in paragraph 7, to the effect that the levels of unreliability in peacetime have not been such as to intérfere significally with the training of crews, and hence have not affected their wartime preparedness.

58. The pattern of close support is represented as a demand on each aircraft for bursts of intense flying activities. Each of these consist of a sequence of sorties that are spaced as closely as possible in time. Each sequence is seen as a response to some critical event in the land battle, such as an armoured breakthrough or other suitable target concentration. The sequences are taken to be spaced at comparatively large intervals of time, so that the sorts of maintenance activities that can be undertaken within a sortie turnround are very different from those that are possible between sequences. The number of sorties in a sequence is treated parametrically.

59. Measure of effectiveness. The function of a tactical air force is assumed to be to destroy surface targets, of a small number of generic types (eg tanks). The effectiveness is taken to vary in proportion to the total number of such targets destroyed by the force during a battle. In these terms, loss of effectiveness will depend upon both.

a. attrition of the air force, or other damage, inflicted by enemy action,

b. unavailability of aircraft or equipment due to scheduled maintenance activities.

c. incidence of defects due to unreliability.

To a first order approximation it is reasonable to assume that the occurrences of (a) are independent of those of (c). Their effects, however, may well interact, but, as an initial assumption, these are also taken to be independent of one another. A further simplification to the analysis can be made by transferring the effect of (b) to support costs; ie by allowing for the extra resources (eg rotable spares) to be provided to ensure that scheduled activities have a negligible impact in comparison with randomly occurring defects. In the cases studied, the consequent increase in life support cost would be only a small percentage. The effectiveness,E, is therefore taken as the following ratio:

$$E = \frac{\text{targets destroyed at a given level of R \& M}}{\text{targets destroyed given perfect reliability}}$$

- - - equation 1.

60. All defects observed on the individual sub-systems of the aircraft are grouped into the following three classes:

<u>Type 1.</u> Defects that, in wartime, would prevent take-off, or, if occurring whilst airborne, would require an immediate return to base.

<u>Type 2.</u> Defects that would not prevent take-off in wartime but would degrade the ability to destroy targets.

<u>Type 3.</u> Defects that have no influence on mission capability.

It is assumed that repairs of all Types 1 and 2 defects can be made between sequences but that <u>none</u> can be made in the intervals between sorties. As an example, a 3-sorties per-sequence operation is shown in Figure 9.

61. <u>Further assumptions.</u>

(i) Whenever a Type 1 defect occurs in a sequence, the aircraft will remain out of action until the end of that sequence.

(ii) Duration of weapons release period is small compared with sortie length, and occurs mid-way through the sortie, as shown in Figure 9. (This simplifying assumption is not critical. Provided total weapon release time remains small, releases could be treated as though spread across the sorties, without substantially changing the results from the model).

(iii) On each occurrence of a Type 2 defect on a particular aircraft a reduction coefficient, α, is applied to the expected number of targets destroyed by its next weapons release. (This coefficient is used to represent the average degradation produced by all types of defect. It is treated parametrically).

(iv) Turn-round times allowed between sorties are too short for repair of Type 2 defects. These are therefore carried over from sortie to sortie, within a sequence. If a number, m, of Type 2 defects has accumulated before a weapon release period, the factor α^m is therefore applied to the expected number of kills during that period.

(v) Types 1 and 2 defects are fully repaired in the intervals between sequences.

(vi) Types 1 and 2 defects occur at random during the sorties, independently of one another.

(vii) At the beginning of the first sequence of the battle, there are no aircraft unserviceable, due to unreliability.

62. <u>Derivation of the effectiveness ratio (E).</u> This follows from the foregoing assumptions, using the following notation:

λ_1 = expected number of Type 1 defects per sortie

λ_2 = " " " " 2 " " "

α = degradation factor (para 59 (iii) and (iv))

n = number of sorties in a sequence ,

Of those aircraft flyable at the start of a sequence, the proportion reaching the point of weapons release in the j^{th} sortie is given by

$$\exp\left[-(j-\tfrac{1}{2})\lambda_1\right]$$

For such aircraft, the effect of Type 2 defects on the expected number of targets destroyed during the j^{th} sortie is given by multiplying by the following factor

$$\left[1 + \alpha(j-\tfrac{1}{2})\lambda_2 + \frac{\alpha^2(j-\tfrac{1}{2})^2\lambda_2^2}{2!} + \text{- - -}\right]\exp\left[-(j-\tfrac{1}{2})\lambda_2(1-\alpha)\right]$$

Thus, each unit expectation at the j^{th} weapon release has been reduced by the Type 1 and Type 2 defect rates to:

$$\exp\left\{-(j-\tfrac{1}{2})\left[\lambda_1 + \lambda_2(1-\alpha)\right]\right\}$$

Substituting x for $\frac{1}{2}\left[\lambda_1 + \lambda_2(1-\alpha)\right]$ and summing over all sorties in the sequence, it follows from equation 1 that

$$E = \frac{1}{n}\sum_{j=1}^{j=n}\exp\left[-(2j-1)x\right] \text{ - - - equation 2}$$

$$\therefore\ \underline{E = (1-e^{-2nx})/2n\,\mathrm{SINH}x \text{ - - - equation 3}}$$

63. The estimated loss of effectiveness due to unreliability is given by 100(1-E)%, and is plotted against

Type 1 defect rate, λ_1, in Figure 10, in which the effects of varying the degradation factor, α, the sequence length, n, and the ratio λ_2/λ_1 are also shown.

64. Further development of the model (and additional data required) would be influenced to some extent by the ranges of λ_1 and λ_2 that are expected to be of interest. Apart from this, the relative insensitivity to α, over quite a wide range, suggests that over-elaboration should be particularly avoided when the time comes to represent the degradations due to individual sub-systems, (eg when replacing α by a set of distributed variables). The effects of changing the length of sequence are large enough to suggest the need to take a closer look at repair times, perhaps introducing a set of distributed variables to represent them in the next version of the model.

DEALING WITH PROPOSED EXTENSIONS TO TIME SCALE

65. Perhaps the most intractable problem encountered in studies of R & M investments and returns is how to put a value on delays to in-service dates. The question arises because some of the means of R & M enhancement that suggest themselves in development or early production require additional time, despite a more intense use of other resources. On what can an operator of airborne weapons system base a decision when informed that if, for instance, he waits another year for some new equipment, it will save x million dollars of support costs and give a y% increase in operational effectiveness when it gets into service?

66. It seems reasonable to start from the assumption that the delay would require an extension of life (and, perhaps, additional quantities) of obsolescent equipment, and that this would perform the required functions at a higher cost during the period of delay than would the new equipment. In the case of an airborne weapons system, an estimate of this cost difference might help the decision-maker, but seems to be inaccessible. I believe this is because the underlying trends in the cost/effectiveness of weapons systems tend to be masked, mainly by changes in the description of the threats that they are intended to meet.

67. An example of the sort of trend that might be uncovered is given by the costs of carrying unit weight of payload in air transport operations which, it can be argued, serves to 'isolate' savings that are almost wholly due to the 'march of technology'. The data given in Reference 6, for civil air transport, are shown in Figure 11. They suggest that, by a more or less continuous process, (with a slight discontinuity following the introduction of jet aircraft in 1958), the effectiveness/cost ratio was doubled during the 20 years period up to 1973. Each of the major components of cost showed a similar trend.

68. It is for consideration whether the corresponding trends are accessible in the case of airborne weapons system (eg in anti-tank capability per unit cost) and, if so, what techniques should be used to convert them into estimates of equivalent cost penalties for given delays in the introduction of new systems.

ANALYTICAL SUPPORT FOR THE CONDUCT OF PROJECTS

69. The techniques by which investments in activities for improving R & M are brought to bear throughout projects have been enumerated elsewhere. The UK Ministry of Defence publication at Reference 6 deals with integrated management of R & M in avionics projects from the initiation of the concept through to maturity in service. In the USA, Military Standards of the 785 series have given precepts for the management of R & M that are applicable at the level of whole airborne weapons systems.

70. Trade-off's play a very important part in the management of R & M activities. For example, preliminary studies can indicate the potential for trading reliability and maintainability with 'performance' variables, or with time-scale. These must draw heavily on systematically exploited 'feed-back' from earlier projects, but can be up-dated as better data become available during the conduct of the project. The accommodation of several kinds of avionics equipments in the confined space and usually 'difficult' environment of the aircraft is another area for trade-off. Selection of priorities for funding additional R & M activities is required throughout a weapons system project, in terms of both the techniques to be preferred and the sub-systems to be given most attention. In many areas of airborne weapons system technology, R & M activities have already reached a high level of refinement in recent projects. The UK studies mentioned earlier (paragraph 5) have shown that good returns are feasible from additional R & M investment in future projects provided that the choice of points of application, and of the most appropriate sub-system, is shrewdly made during all the phases shown in Figure 1.

71. During later development, transition to production, early production and early service, huge quantities of R & M data become available in an airborne weapons system project. Their acquisition and processing to aid timely decisions aimed at meeting, or revising, R & M objectives/forecasts poses a considerable challenge. As discussed in paras 21-25, it is during these phases that the main threats to reliability and maintainability, and specific counter measures reveal themselves, or are confirmed. Together with the trade-off analyses of para 69, above, the data acquisition and analysis constitute a need for a coherent information service.

72. Because of differences in required capabilities, in technologies available at the time, and in ultimate operational usage, there is still considerable room for improving the bases for:

a. setting reasonable targets for R & M at the outset of a project

b. comparing the R & M achievements at the various stages of a project with those from earlier projects, to indicate the progress being made in this respect.

73. It is seen that the control of life-cycle costs in future projects is likely to benefit greatly from improved means for acquiring and interpreting data. The main requirements for analytical support (ie a kind of "R & M information service") for the management of a major project, in these respects, are illustrated in Figure 12.

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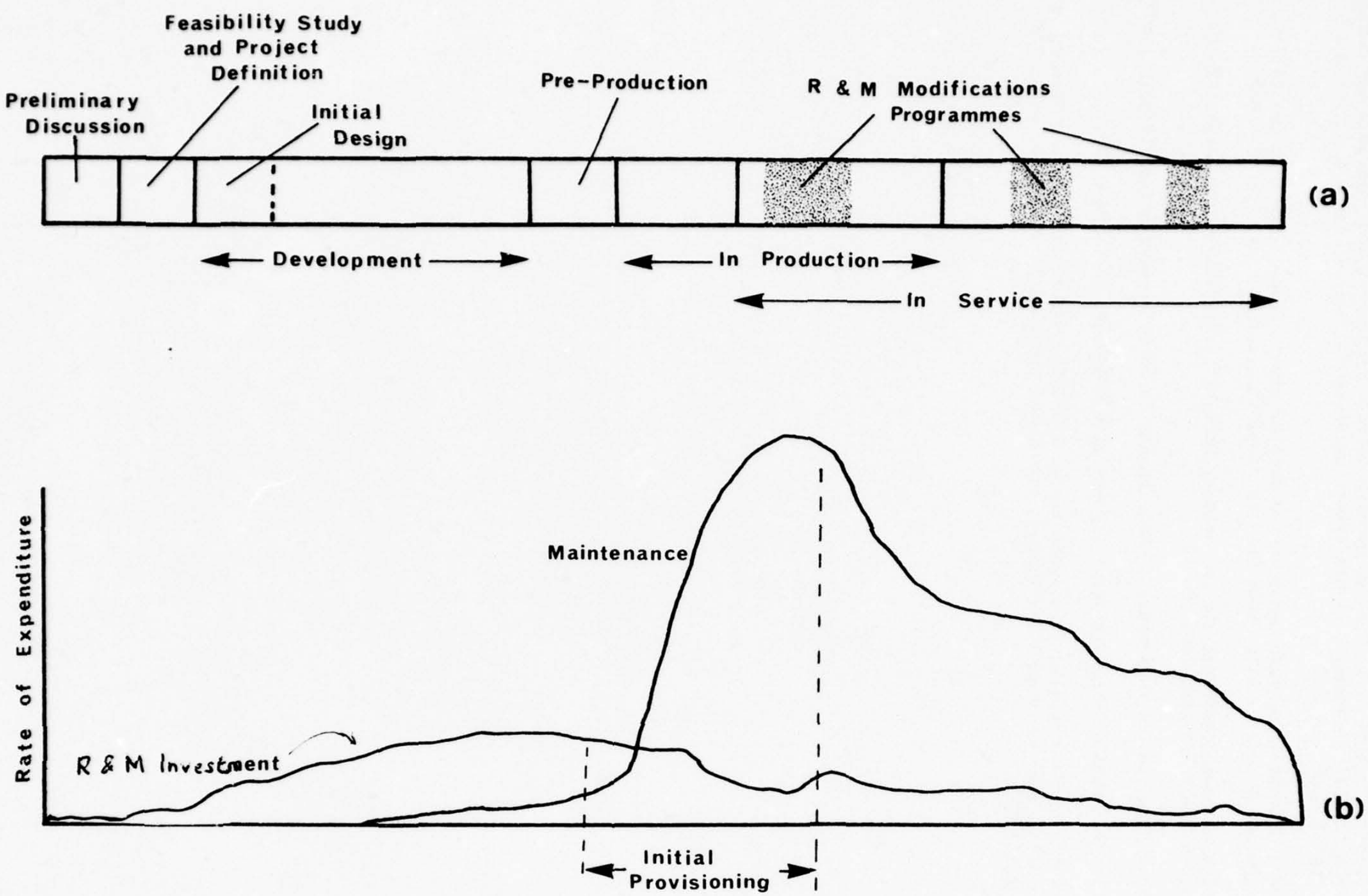


Figure 1 (a) Project phases

(b) Expenditure associated with R & M (notional)

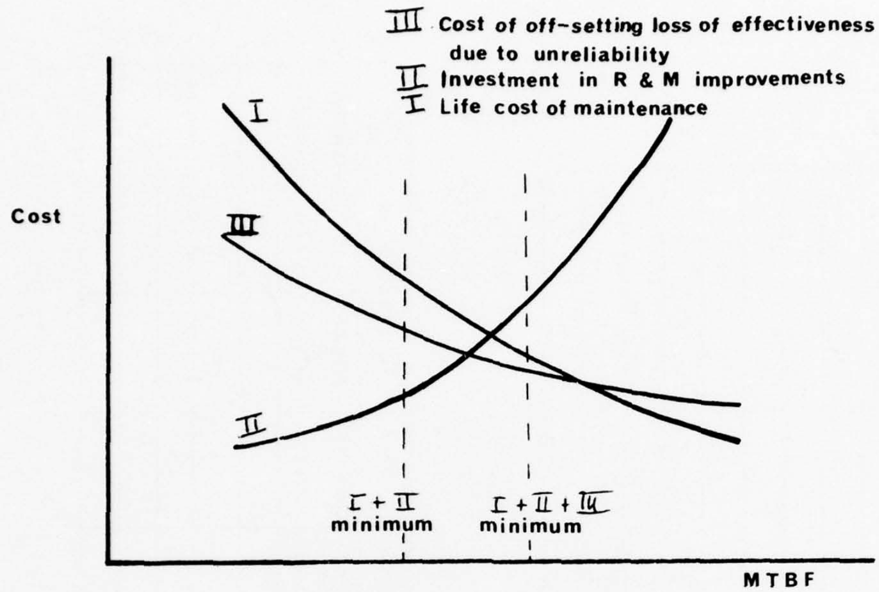


Figure 2 Shift in estimate of optimum MTBF when operational effectiveness taken into account

SUB-SYSTEM	AIRCRAFT TYPE						
	A	B	C	D	E	F	MISC
ELEC. SUPPLY	✓	-	-	-	-	-	-
NAV/WEAPON-AIMING	-	✓	-	-	-	-	-
HUD	-	✓	-	-	-	-	-
ILS RECEIVER	-	✓	✓	-	✓	-	-
AI RADAR	-	-	✓	-	-	✓	-
TRANSPONDER I	✓	✓	✓	✓	-	-	✓
TRANSPONDER II	-	-	-	-	✓	✓	-
INTERROGATOR D/F	-	-	-	✓	-	-	-
SONOBOUY	-	-	-	✓	-	-	-
PROPULSION	✓	✓	-	-	-	-	-
HYDRAULIC	✓	✓	-	-	-	-	-
AIR CONDITIONING	✓	✓	-	-	-	-	-
FUEL	✓	✓	-	-	-	-	-

Figure 3. Sub-systems chosen for studies

(a)

INVESTMENTS IN R & M IMPROVEMENT

PHASE		DIRECT LABOUR	FACILITIES & MATERIALS	OTHER OVERHEADS
CONCEPTUAL STUDIES				
INITIAL DESIGN				
FURTHER DEVELOPMENT				
DEVT. → PRODUCTION				
PRODUCTION				
IN-SERVICE MODNS.	Development			
	Production			
	Incorporation			

(b)

RELIABILITY-DEPENDENT MAINTENANCE

		SCHEDULED MAINTENANCE ACTIVITIES				REPAIR OF DEFECTS			
		On flight -line	Hangar or bay	At depot	Within industry	On flight - line	Hangar or bay	At depot	Within industry
ON-GOING SUPPORT	Direct labour								
	Consumable spares & materials								
	Running overheads								
FIXED OUTLAY SUPPORT	Rotable spares								
	Test equipment etc								

Figure 4. Itemization of R & M – associated costs

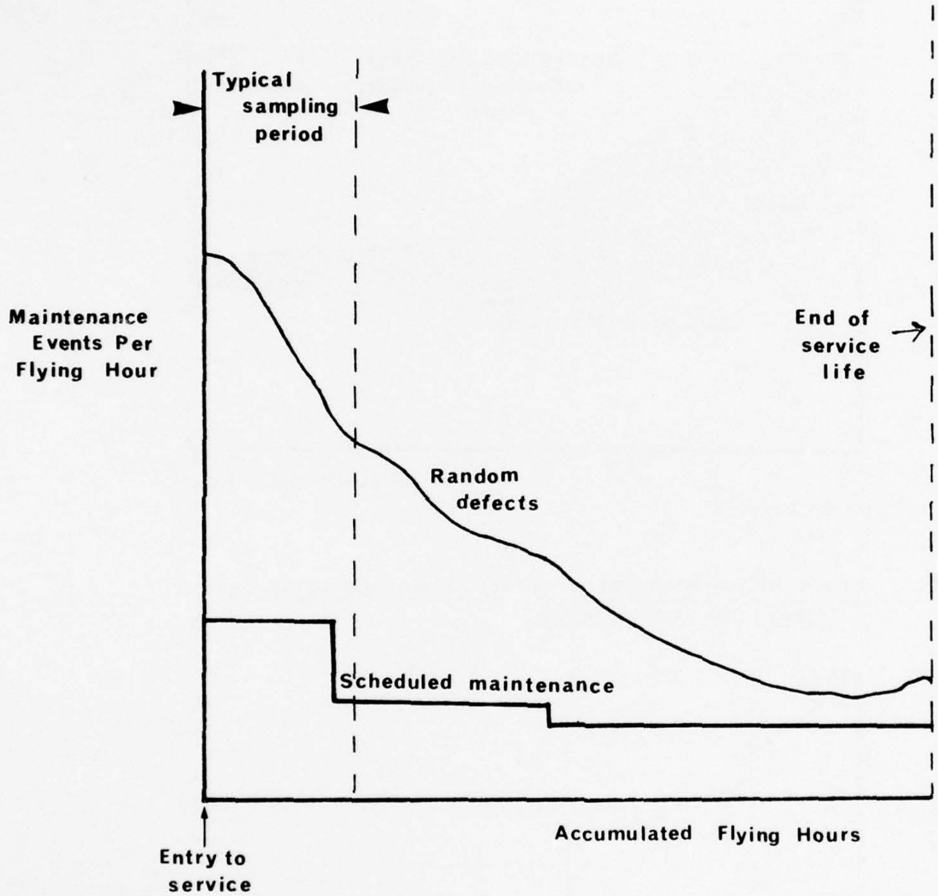


Figure 5. Life-cycle trends in rates of maintenance events

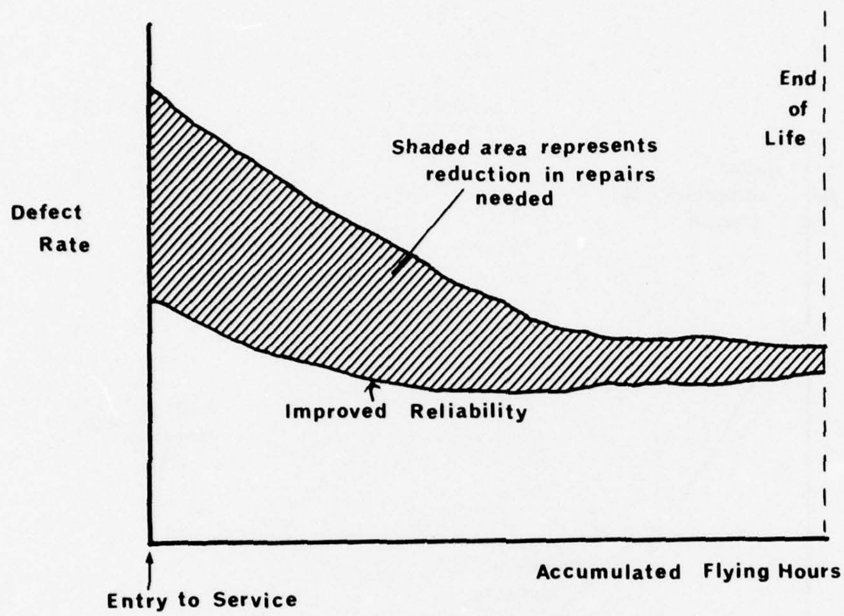


Figure 6. Effect of improvement in reliability on the on-going demand for maintenance

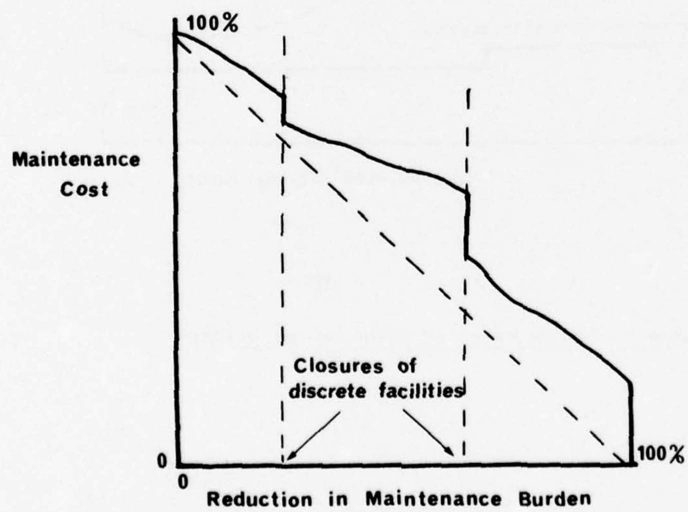


Figure . 7 Relation between reduction in maintenance load and cost savings , (Notional)

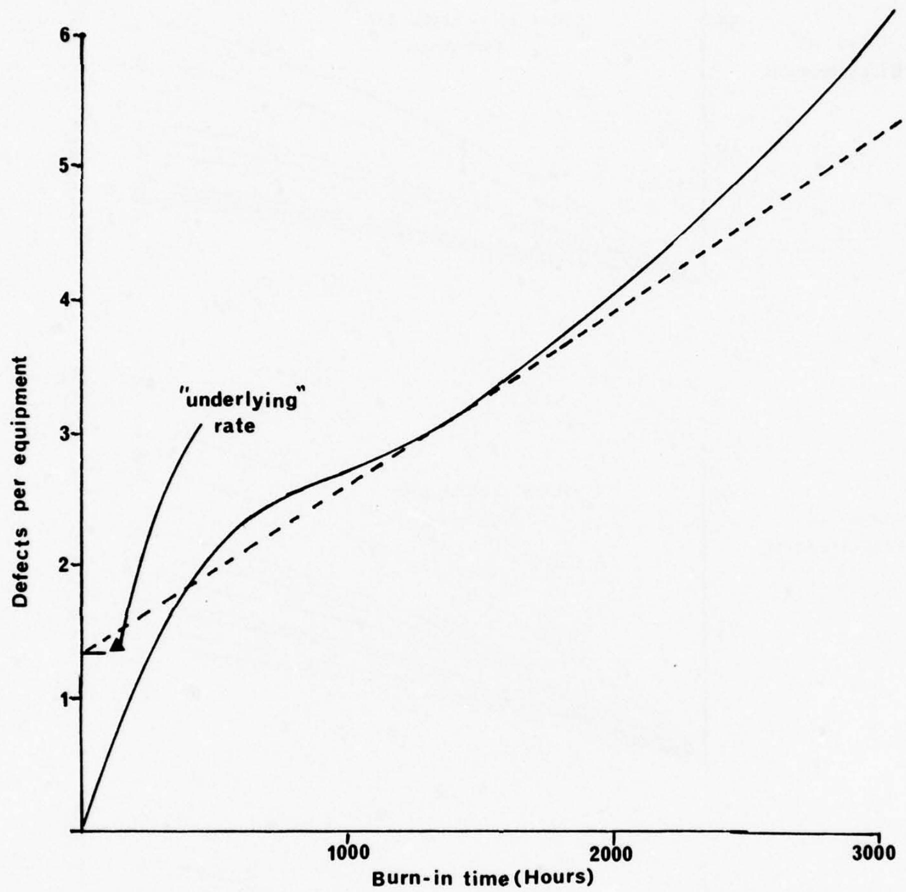


Figure 8. Observed effect of prolonged burn-in

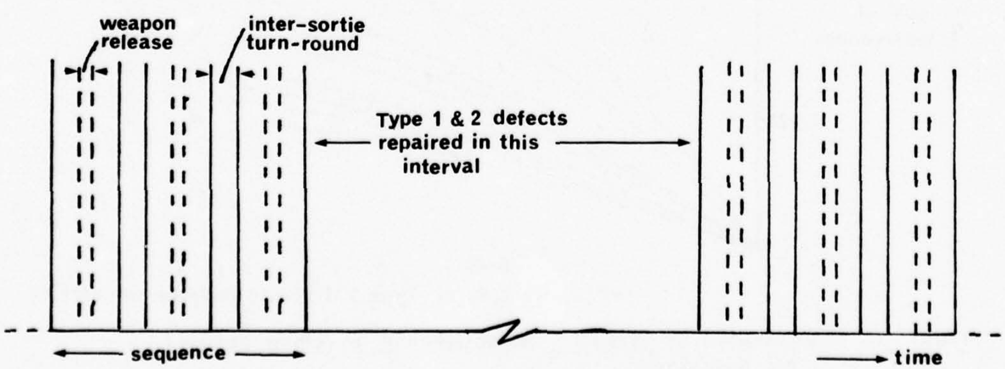


Figure 9. Illustration of 3-sortie-sequenced close air-support operations

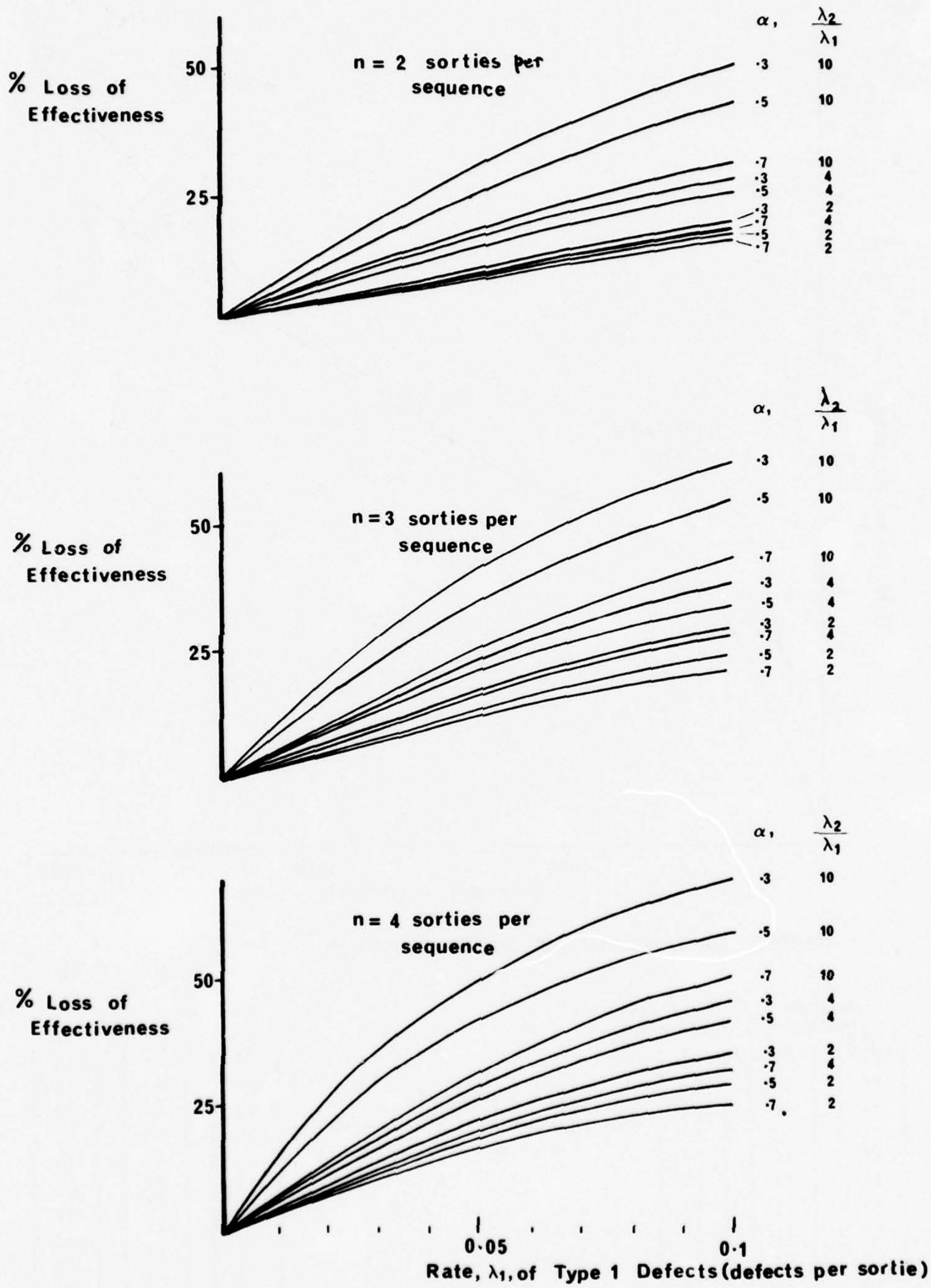
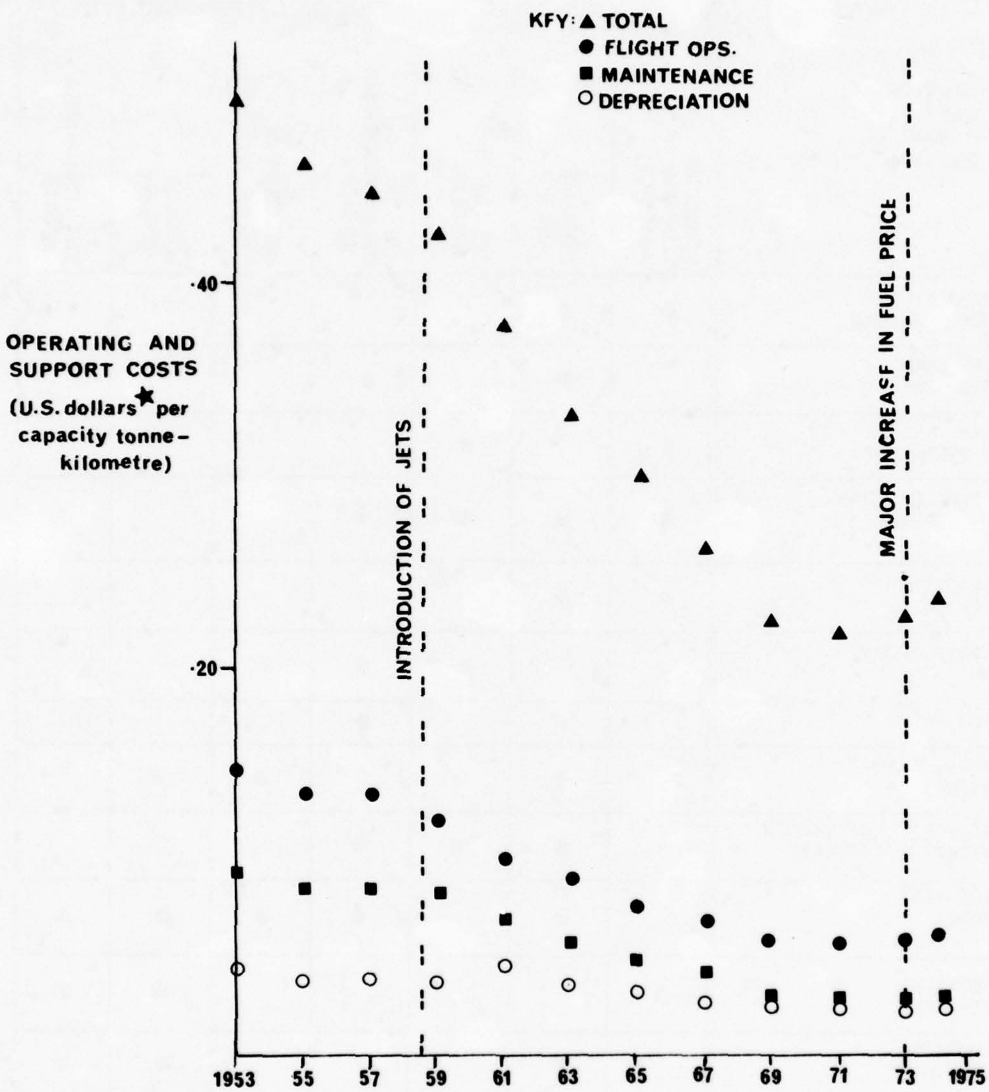


Figure 10 Estimates of loss of effectiveness in close support air operations



(* Adjusted for inflation to 1975 prices)

Figure 11 Trends in airline operating costs

	FUNCTIONAL PARTS OF R&M PROGRAM	ANALYTICAL SUPPORT CAPABILITIES REQUIRED: DEVELOPING STANDARDS OF REFERENCE	TRADE-OFF STUDIES	UPDATING OF FORECASTS	COST/EFFECTIVENESS STUDIES	ASSESSMENT OF OVERALL R&M PLANS	LOGISTIC STUDIES	FIELD INFORMATION SERVICE
Conception and launching	SETTING INITIAL TARGETS FOR R&M	●	●					
	MAKING BASIC TRADE-OFFS		●		●			
	PRELIMINARY R&M FORECASTING	●		●				
	R&M SPECIFICATIONS IN CONTRACT	●	●	●	●			
Development and production	CONTRACTORS "OVERVIEW"	●	●					
	CONTRACTORS R&M PLAN			●	●	●		
	DESIGN REVIEW				●			
	PERIODIC PROGRAM REVIEWS		●	●	●	●	●	
	RE-ALLOCATION OF TARGETS & UPDATING FORECASTS		●	●	●			
	FLIGHT-TEST PROGRAM		●		●	●	●	●
In-Service	IN-SERVICE FEED-BACK	●					●	●
	IN-SERVICE IMPROVEMENT		●		●		●	●

FIG 12(a) Points of application of analytical support for R&M program of major project

FUNCTIONAL PARTS OF RELIABILITY AND MAINTAINABILITY PROGRAM

Initial targets	Basic trade-offs	Preliminary forecasts	Specifications for contract	Contractors' "Overview"	Contractors' R&M plan	Design review	Program reviews	Re-allocation of targets	Flight-test program	In-service feed-back	In-service improvement
Tentative formulation of R&M objectives.	Treatment of R&M on a par with "performance" variables. Anticipation of interactions of sub-systems.	Apportionment of reliabilities, and modelling reliability of total system in the light of results from feasibility studies.	Statement of R&M requirements; guidance on contractual responses expected, particularly on the proposals for R&M program plan.	Review by prime contractor of the total requirements, followed by detailed reappraisal of means to deal with R&M.	Submission of proposed R&M plan for assessment, amendment as necessary, and approval.	Critical appraisal of design(s), including for instance, review of such aspects as: Stress analysis, FMEA, Human induced failures, Parts-control, etc.	Periodic revision of R&M tactics, and of funding priorities, in the light of ground-tests of development and production models.	Re-allocation of detailed targets of reliability in the light of test results. Revision of forecast R&M levels and of the implied maintenance requirements.	Demonstration of R&M achieved. Continuation of R&M growth in the light of test results. Revision of forecasts of R&M levels in-service, and of maintenance requirements.	Continued demonstration of achievements. Provision of information to guide policies for maintenance procedures and R&M levels.	Selection of priorities in modifications programs; further rationalization of logistics.

ANALYTICAL CAPABILITIES REQUIRED IN SUPPORT

REFERENCE STANDARDS

Development of bases for measuring R&M achievement, including allowances for operational and technical differences. Collation of all relevant data, to estimate the levels attainable and to give references against which current achievements may be compared.

TRADE-OFF STUDIES

Investigation of sensitivities of R&M to Changes in the requirements for 'performance' and time-scale. Estimation of their implication to life - costs and operational effectiveness.

UPDATING OF FORECASTS

Assistance in early recognition, and confirmation, of emergent forms of unreliability, through exploitation of most recent data. Re-estimation of achievable levels of R&M.

ASSESSMENT OF R&M PLANS

Estimation of overall effectiveness of initial program plan (and its later revisions) within given time-scales and resource limitations. Identification of areas in which changes in R&M - investment, or in contractual requirements, will give best returns

COST/EFFECTIVENESS ESTIMATION

Assistance in early identification of the more important defiencies in R&M, (eg based on data from development and production, and on estimates of effects on life costs and loss of operational effectiveness).

LOGISTIC STUDIES

Collection and analysis of data relevant to maintenance requirements, to aid in the choice of repair policies and in quantities of spares and support equipment to be provisioned.

FIELD INFORMATION SERVICE

Participation in planning and conduct of special in-service collections of data. Analysis of these and 'routine' data, to provide basis for rapid selection and approval of priorities.

Figure 12(b) Content of analytical support for R&M program.

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This Bibliography with Abstracts has been prepared to support AGARD Lecture Series No.100 by the Scientific and Technical Information Branch of the US National Aeronautics and Space Administration, Washington, D.C., in consultation with Dr I.J.Gabelman of Rome, New York.

CONTENTS

SECTION 1

COST ESTIMATING RELATIONSHIPS AND MODELING

An analytical method of defining low life cycle cost avionics

A/BLOXON, W. D.; B/KENNEDY, C. D. A/(Boeing Wichita Co., Wichita, Kan.); B/(USAF, Aeronautical Systems Div., Wright-Patterson AFB, Ohio) In: NAECON '78; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 16-18, 1978, Volume 3. (A78-49851 22-04) New York, Institute of Electrical and Electronics Engineers, Inc., 1978, p. 1222-1224.

ABS:The present study provides a basis for defining a modernized strategic avionics system to meet the improved performance and reduced operation and maintenance costs to support strategic operational requirements in the 1980s. The analysis shows that a dramatic cost effectiveness improvement can be achieved over the baseline and that current technology will support the guide requirements for life cycle cost and performance. In order to meet SAC's requirements, the following features are necessary: improved radar resolution; high jamming resistant terrain following radar; good radar performance in weather; radar image freeze; Class I inertial system; low altitude penetration; and redundancy for mission success. ABA:V.P. 78/00/00 78A49990

An effective methodology to implement design to life cycle cost

A/BEZAT, A.; B/BUYSE, R. B/(Honeywell, Inc., Avionics Div., Minneapolis, Minn.) In: NAECON '78; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 16-18, 1978, Volume 3. (A78-49851 22-04) New York, Institute of Electrical and Electronics Engineers, Inc., 1978, p. 1078-1082.

ABS:The paper describes a methodology for implementing design to life cycle cost (DTLCC) developed for avionics hardware. The methodology consists of (1) a unit product cost model, (2) a DDT&E cost estimating technique, and (3) a logistics support cost model. Attention is given to the background and reasons for the methodology selected, specific examples of LCC analyses, and the alternatives considered. ABA:B.J. 78/00/00 78A49970

System avionics value estimation /SAVE/ - A new tool for logistics and support cost analyses

A/HARRIS, R. L.; B/CORK, T. R. A/(USAF, Avionics Laboratory, Wright-Patterson AFB, Ohio); B/(Battelle Columbus Laboratories, Columbus, Ohio) In: NAECON '78; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 16-18, 1978, Volume 3. (A78-49851 22-04) New York, Institute of Electrical and Electronics Engineers, Inc., 1978, p. 1073-1077.

ABS:The SAVE program performs logistic support analysis for avionics using a hierarchy of five special-purpose logistic and support cost models integrated within an interactive framework. The computer framework permits the following: (1) user definition of the hardware configuration up to five levels of indenture, (2) establishment of one consistent data-file for the entire set of models, (3) on-line descriptions of each data item's utilization of the available models, (4) use of an appropriate model for the problem being analyzed, (5) on-line graphical presentation of results, and (6) adaptability to add models beyond the initial set of five. ABA:B.J. 78/00/00 78A49969

Approach for identifying avionics flight software operational support requirements - PAVE TACK an example

A/MONTGOMERY, H. A.; B/TURK, R. L. A/(TRW Defense and Space Systems Group, Redondo Beach, Calif.); B/(USAF, Warner Robins Air Logistics Center, Robins AFB, Ga.) In: NAECON '78; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 16-18, 1978. Volume 1. (A78-49851 22-04) New York, Institute of Electrical and Electronics Engineers, Inc., 1978, p. 418-425.

ABS:An approach is presented for identifying the types of tools required by the Air Force Logistics Command (AFLC) to support an avionics flight program over its operational life. This approach involves an analysis of the avionics system with respect to the phases of the software life cycle. Characteristics of avionics systems are identified which contribute to an active operational life and have implications for support methods. Operational support requirements are then established from the activity phases of the software life cycle and AFLC operational support objectives. Tool requirements can then be selected from a hierarchy of tools which support the software life cycle. ABA:(Author) 78/00/00 78A49900

Software cost estimating methodology

A/JAMES, T. G., JR. A/(USAF, Avionics Laboratory, Wright-Patterson AFB, Ohio) In: NAECON '77; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 17-19, 1977. (A78-15551 04-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1977, p. 22-28.

ABS:The area of determining the expected cost of software requirements for new and advanced projects, is of ever increasing concern to the Department of Defense, as well as industry. More and more of the development dollar is being spent for software support rather than for advanced hardware developments. The costs associated with hardware continue to decrease (or at least are leveling off) with the introduction of new and better production

techniques. Software costs on the other hand are continuing to rise, due primarily to increased personnel costs. The cost analysts of today are not only faced with predicting or estimating hardware costs (total life cycle costs), but are also expected to derive an estimate for software development costs, and software life cycle costs. This paper reviews several software cost estimating 'models' which exist today. ABA:(Author) 77/00/00 78A15555

HOL vs. AL for avionic software
A/HAYS, G. G. A/(Westinghouse Electric Corp., Baltimore, Md.) In: NAECON '76; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 18-20, 1976. (A77-37352 17-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1976, p. 716-722.
ABS:This paper will discuss the balanced design trade-offs that were done in making the decision to use an HOL over assembly language on a large avionics project. Ease of design, documentation problems, test considerations and maintainability reflected in life cycle costs are the major factors that were traded. The general requirements of an HOL suitable for operational software development will be reviewed. With the cost of hardware (mainly computer memories) coming down and the cost of labor (mainly software engineers) going up, the luxury of ultra efficient hardware usage at the expense of people's time is coming to an end. A new era of putting emphasis on saving labor dollars is emerging. HOLs save people's time in all areas of the pre-design, debug, testing and documentation. But HOL's use more hardware and, as yet, are not standard. ABA:(Author) 76/00/00 77A37444

A standard life cycle cost model for inertial systems
A/DEBURKARTE, D. E. A/(Rockwell International Corp., Collins Radio Group, Cedar Rapids, Iowa) In: NAECON '76; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 18-20, 1976. (A77-37352 17-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1976, p. 687-695.
ABS:The paper describes the life cycle cost model for inertial systems developed by the Life Cycle Cost Task Group of the Joint Services Data Exchange for Inertial Systems. The model, the key concept of which is flexibility, permits inputs ranging from comprehensive sets of detailed data to gross estimates of total categories. It also makes available a package of 'canned' output reports as well as the totally defined output data table which allows each user to substitute his own output reports generator to meet unique data/format requirements. ABA:B.J. 76/00/00 77A37440

O & M cost estimation from basic design parameters
A/ENGEL, H. E.; B/CZUCHRY, A. J.; C/BARAN, H. A.; D/DIETERLY, D.; E/STAUFFER, R. B. B/(Dynamics Research Corp., Wilmington, Mass.); D/(USAF, Human Resources Laboratory, Wright-Patterson AFB, Ohio); E/(J & R Associates, Jackson, N.H.) In: NAECON '76; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 18-20, 1976. (A77-37352 17-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1976, p. 682-688.
ABS:A model is described that provides estimates of operation and maintenance costs to be made during the conceptual design phase of new avionics equipment procurement. Cost and policy, mission scenario, manpower, logistics and design data are processed in appropriate combinations. Results are obtained through a set of estimating relationships to create an intermediate set of values descriptive of the reliability and maintainability characteristics of the hardware. These are then further processed by a set of algebraic equations to generate actual cost values. The relationships between costs, the characteristics of the design and environment, and reliability and maintainability are clearly identified. The user can then readily determine significant cost drivers among the parameters and identify the design, logistics and manpower factors to alter in order to attain desired cost reduction. ABA:(Author) 76/00/00 77A37439

The flexible analysis, simulation, and test facility - A practical software-first capability
A/PRESS, B.; B/MCCLEAN, R. K. B/(TRW Defense and Space Systems Group, Redondo Beach, Calif.) In: NAECON '76; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 18-20, 1976. (A77-37352 17-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1976, p. 264-268.
ABS:Diagnostic emulation, based on microprogram emulation technology, is discussed as a way to reduce high costs in the development and verification of highly reliable aerospace software. This technique is shown to be significantly more cost effective than conventional interpretive computer simulation for performing software checkout and testing. A computer description language is shown to be essential for developing diagnostic emulators. The development of the Flexible Analysis, Simulation and Test (FAST) facility on the basis of diagnostic emulation is discussed. ABA:B.J. 76/00/00 77A37386

An analysis of cost of ownership
A/DE BARROS, R. A/(SABENA Belgian World Airlines, Brussels, Belgium) In: Symposium on Equipment and Systems Design for Minimum Cost of Ownership, London, England, March 16, 1976, Proceedings. (A77-22751 08-83). London, Royal Aeronautical Society, 1976, 12 p.; Discussion, p. A1-A10.
ABS:Life cycle costing is proposed as a suitable approach to make decisions about system acquisition since it is based on the total projected cost of the system over its useful life. Three main phases are relevant in the whole projected period: development, production, and operating. The airline is concerned primarily with the operating phase. The paper analyzes the operating costs of a typical avionic system projected over a period of twenty years regarded as a normal duration of a jet fleet. It is assumed that the evaluation period starts with the first airplane and terminates when the last unit of the fleet is sold or scrapped. Results are presented for a simulation analysis of a typical case to find the influence of the various parameters on the operating costs and to point out the possible areas of improvement ABA:S.D. 76/00/00
77A22753

A logistics analysis and ranking model /ALARM/
A/DAVIDSON, W. L.; B/LANDSTRA, B. J. B/(Hughes Aircraft Co., Canoga Park, Calif.) In: Annual Reliability and Maintainability Symposium, Washington, D.C., January 28-30, 1975, Proceedings. (A75-44202 22-38) New York, Institute of Electrical and Electronics Engineers, Inc., 1975, p. 538-542.
ABS:ALARM is a support cost model useful for the following purposes: computation of life cycle support costs for a system composed of replaceable subassemblies; determination of the most cost effective of alternate design concepts; analysis of the sensitivity of support costs to changes in system design parameters; selection of the most economical of four specified maintenance concepts; identification of the highest cost components and support elements of a system. The model is complete and operational, and has been used effectively in the evaluation of support of a complex airborne avionics system. This model produces life cycle support cost information which is essential for evaluating approaches for maintaining an equipment system. This information is provided in clearly defined reports produced by the model on demand. ABA:(Author) 75/00/00
75A44245

Cost of ownership - An overview: Life cycle costs - Evaluation of avionic system reliability improvements
A/BRODE, H. A. A/(Hughes Aircraft Co., Canoga Park, Calif.) In: Annual Reliability and Maintainability Symposium, Washington, D.C., January 28-30, 1975, Proceedings. (A75-44202 22-38) New York, Institute of Electrical and Electronics Engineers, Inc., 1975, p. 212-216.
ABS:A definition of life cycle cost is provided and an avionics life cycle cost model is presented. Two computer programs are utilized. One model generates development and investment phase costs. Another model computes operating and investment phase support costs. The output of both models is combined into one computer printout. Attention is given to the calculation of maintenance resource requirements, study ground rules and assumptions, and life cycle cost results. It is shown that it is possible to reduce the life cycle cost significantly. ABA:G.R. 75/00/00 75A44219

System Avionics Value Estimation (SAVE): An aid for avionics logistics-and-support-cost analyses
A/CORK, T. R.; B/MULCAHY, J. F. Battelle Columbus Labs., Ohio.
ABS:This report documents a research effort to develop an interactive graphics computer system which will allow government cost analysts to exercise five existing logistics and support cost models in an integrated, consistent, and efficient manner. ABA:GRA
AD-A056348 AFAL-TR-77-179 77/09/00 78N33097

The feasibility of estimating avionics support costs early in the acquisition cycle. Volume 1: The basic report
A/MORGAN, J. D.; B/FULLER, A. B. Institute for Defense Analyses, Arlington, Va. (Cost Analysis Group.)
ABS:This paper reports on research to determine the feasibility of developing methods to estimate, early in the system acquisition cycle, the potential support cost inputs of alternative avionics components envisioned for Air Force and Navy fighter aircraft. Support costs are defined as those costs incurred at the organizational, intermediate and depot levels to maintain avionics equipment and the costs of avionics spares and repair parts support. The results of the study are presented in two volumes. Volume I reviews and evaluates current methods used in industry and in the Air Force and Navy to estimate these avionics support costs. Finally, the paper concludes that it is feasible and desirable to prepare these estimates for avionics support costs. The specific method to be adopted depends on the amount of resources OSD wishes to devote to this effort. Volume II is a compilation of appendixes containing additional material to support the basic report.

including summary evaluations of forty-eight key documents encountered in the literature search. ABA:GRA
AD-A054016 AD-E500025 P-1292-VOL-1 77/09/00
78N30119

The feasibility of estimating avionics support costs early in the acquisition cycle. Volume 2: Appendixes
A/MORGAN, J. D.; B/FULLER, A. B. Institute for Defense Analyses, Arlington, Va. (Cost Analysis Group.)
ABS:This paper reports on research to determine the feasibility of developing methods to estimate, early in the system acquisition cycle, the potential support cost inputs of alternative avionics components envisioned for Air Force and Navy fighter aircraft. Support costs are defined as those costs incurred at the organizational, intermediate and depot levels to maintain avionics equipment and the costs of avionics spares and repair parts support. Volume 2 is a compilation of appendixes containing additional material to support the basic report, including summary evaluations of forty-eight key documents encountered in the literature search. ABA:GRA
AD-A053486 AD-E500026 P-1292-VOL-2 IDA/HQ-77-19873
77/09/00 78N28093

Economic analysis of future civil air navigation systems
A/JOGLEKAR, A. N.; B/SEILER, K., III Mitre Corp., McLean, Va. (Metrek Div.)
ABS:The economic analyses of three previous FAA/METREK studies related to future domestic air navigation are updated and consolidated. The Airway Facilities Service made significant revisions to both the F&E and O&M cost estimates for VORTAC modernization. The FAA also updated its estimate of distribution of VOR and DME among the general aviation population. This report documents the impact of these changes. The study shows that there is no cost advantage in replacing the present VOR/DME system unless more stringent needs, such as area navigation, coverage and accuracy become necessary. Based on the estimated avionics costs the results show that the total cumulative costs (discounted at 10%) to the user plus government, for the various alternatives studied from the year 1985-2010, range from $695 million for VOR/DME, and $865 million for LORAN-C, to $970 million for GPS. It is further shown that if either LORAN or GPS ever became the primary air navigation system, then keeping the VOR for general aviation for a lengthy transition period would be economically attractive. ABA:G.Y.
AD-A054474 FAA-EM-78-6 77/12/00 78N28078

Cost reporting elements and activity cost tradeoffs for defense system software. Volume 1: Study results
A/GRAVER, C. A.; B/CARRIERE, W. M.; C/BALKOVICH, E. E.; D/THIBODEAU, R. General Research Corp., Santa Barbara, Calif.
ABS:In April 1976, General Research Corporation (GRC) began a study of 'Life-Cycle Costing of Major Defense System Software and Computer Resources.' Contract F19628-76-C-0180. The purpose was to assist Air Force Program Offices and staff agencies in estimating, reporting and controlling the life-cycle costs of software. The study was performed under direction of the Electronic Systems Division (AFSC), Computer Systems Engineering Office (TOI).
ABA:CRA
AD-A053020 CR-1-721-VOL-1 ESD-TR-77-262-VOL-1 77/05/00
78N25971

A preliminary calibration of the RCA price S software cost estimation model
A/SCHNEIDER, J., IV Air Force Inst. of Tech., Wright-Patterson AFB, Ohio. (School of Engineering.)
ABS:Each year, the Department of Defense spends more than three billion dollars on computer software, yet software managers are notoriously unable to predict the cost of software development projects. This is especially true of preliminary cost estimates made during the *formative* stages of a project. Even when parametric relationships are used, such estimates depend heavily on analogy with previously developed systems. The purpose of this research is to investigate ways of gathering and using descriptive data for the purpose of making preliminary software cost estimates. A methodology for the collection of descriptive information on software systems was developed and used to describe several avionics software systems. The data thus gathered was then used to 'calibrate' the PRICE S software cost estimation model by relating particular values of several 'subjective' PRICE S input parameters to the observed software system data. It was found that certain characteristics of software systems could be objectively measured, and that the PRICE S model is not incompatible with avionics software systems developed for the Aeronautical Systems Division of Air Force Systems Command. ABA:Author (GRA)
AD-A046808 AFIT/GSM/SM/77S-15 77/09/00
78N15740

Avionics data for cost estimating
A/ARMSTRONG, B. E. RAND Corp., Santa Monica, Calif. Presented at the 1976 DoD Cost Analysis Symp., Airlie, Va., 14-17 Nov. 1976
ABS:Avionics cost has been a continuing problem to the defense cost analyst. The various services and the Office

of the Secretary of Defense (OSD) have sponsored numerous avionics data collection efforts, as well as funding various companies to develop cost models and cost estimating relationships. To mention a few, both the Air Force and the Navy, and research firms such as General Research Corporation (GRC), Research Management Corporation (RMC), and Institute for Defense Analyses (IDA), have all been involved at one time or another with efforts to develop the avionics cost estimation methods and a supporting data bank. The reason for this level of effort is that the costs of avionics account for nearly 30 percent of the total costs of fighter aircraft and a significant amount in most other aircraft types. Yet, because of rapid technological change, typically small production runs, and poor historical cost information, reliable prediction of avionics costs has been impeded. This paper discusses a recent Rand study sponsored by OSD/Director of Planning and Evaluation (DP and E) which had the objective of creating an avionics data base for tactical aircraft. ABA:GRA

AD-A043265 P-5745-1 77/03/00 77N32146

Avionics evaluation program: Multiple aircraft, multiple sorties and cost accumulation

A/BROWN, R. A. Battelle Columbus Labs., Ohio.

ABS:An updated version of the air-to-ground Avionics Evaluation Program (AEP) has been developed. The AEP provides a mechanism for assessing the mission impact of varying avionics hardware configurations. This program is a Monte Carlo simulation of a flight of aircraft (up to four) through a specified number of days of operation. Functions considered include ground maintenance, communication, navigation, refueling, target acquisition, and weapon delivery. The present effort incorporated imperfect equipment monitoring, multiple aircraft, multiple sorties, and cost accumulation. The previous framework for consideration of hardware reliability and backup modes has been retained. The interactive graphics processor has been updated. A more convenient technique for accessing hardware and function data has been incorporated. More flexibility has been added to the output processor to allow selective display of simulation results. ABA:Author (GRA)

AD-A037195 AFAL-TR-76-196 77/01/00 77N26133

A computer model for estimating development and procurement costs of aircraft DAPCA-III

A/BOREN, H. E., JR. RAND Corp., Santa Monica, Calif.

ABS:The report describes and lists an updated computer model (DAPCA-III) that computes from parametric relationships the development and procurement costs of two major flyaway subsystems of an aircraft--airframes and engines. Avionics costs are included but are treated as throughputs. Cumulative average, unit, and total flyaway costs are obtained for up to ten specified aircraft production quantities. Flight and avionics procurements are allowed. Although costs of spare engines are not considered to be flyaway costs, they are calculated in the model as additional costs not included in the totals. Unless otherwise specified, all costs are calculated in 1975 dollars. ABA:GRA

AD-A025276 R-1854-PR 76/03/00 77N12929

Aeronautical economic escalation indices

A/JACKSON, B.; B/LENTZSCH, C. Aeronautical Systems Div., Wright-Patterson AFB, Ohio.

ABS:An attempt is made to forecast price level indexes of the aerospace industry taking under consideration the unprecedented inflation of 1973 - 1974 and its impact on the economic environment of the industry and the weapon acquisition process. Historical data for the years 1958-1975 were compiled to develop cost indexes for airframe, engine, and avionics. These data were projected relative to the Wharton Econometric Unit prediction of GNP deflator for years 1975-1983 to generate the forecasted indexes. Overhead was included to reflect this cost element's influence on total industry cost. Economic escalation due to inflation received the most priority and concern given the austere budgetary environment confronting the Department of Defense. ABA:Author

AD-A022795 ASD-COST-RES-110B 75/07/00 76N32060

Cost-estimating relationships using linear, log-linear and non-linear regression

A/BILIKAM, J. E. Air Force Avionics Lab., Wright-Patterson AFB, Ohio.

ABS:The report addresses the use of weighted regression for linear cost estimating relationships and non-linear regression for log-linear cost estimating relationships with the trends in residual distributions. ABA:GRA

AD-A013928 AFAL-TR-75-43 75/04/00 76N14975

Cost estimating relationships for procurement costs of airborne digital computers and inertial measurement units for use in remotely piloted vehicles

A/FUNKHOUSER, K. V. Air Force Inst. of Tech., Wright-Patterson AFB, Ohio. (School of Engineering.)

ABS:Parametric cost estimating relationships (CER's) are developed to predict procurement costs of airborne digital computers and inertial measurement units which are suitable for use in remotely piloted vehicles (RPV's). The CER's predict first unit recurring cost in 1974 dollars and can be incorporated with an appropriate learning curve to estimate average cost for a given production quantity. A brief discussion of a computerized parametric cost

estimation technique, the RCA PRICE model, is provided to compare methodology, input requirements, and output. The predictive capabilities of the RPV CER's are compared to avionics procurement CER's developed by the Air Force Avionics Laboratory. The RPV CER's are generally more accurate than the AFAL CER's when procurement costs of equipment usable in remotely piloted vehicles are being estimated. ABA:GRA
AD-A003353 GSA/SM/74D-3 74/12/00 75N21277

Joint generalized least squares applied to cost estimation for fighter aircraft
A/OBRIEN, P. W. Air Force Inst. of Tech., Wright-Patterson AFB, Ohio. (School of Engineering.)
ABS:Joint Generalized Least Squares is an extension of least squares techniques which decreases statistical uncertainty in derived regression equations. The technique is applied to historical costs for airframes, avionics, and engines in fighter aircraft. A comparison is made of parametric cost estimating relationships derived using ordinary and Joint Generalized Least Squares to demonstrate reductions in statistical uncertainty. ABA:GRA
AD-A003354 GSA/SM/74D-7 74/12/00 75N21275

Three life cycle cost models for inertial systems
A/ADEL, R. E.; B/BONNER, W. J.; C/GIBSON, K. J. Aerospace Guidance and Metrology Center, Newark Air Force Station, Ohio.
ABS:The purpose of this report was to present three different Life Cycle Cost models for inertial systems to the membership of the Life Cycle Cost Task Group of the Joint Services Data Exchange for Inertial Systems for the purpose of familiarization prior to the April 1974 meeting of that group in Anaheim, California. The report describes three life cycle cost models that have been used in economic analysis of inertial navigation systems. ABA:Author (GRA)
AD-A000483 AGMC-74-011-2 74/04/04 75N17331

A description of a life cycle cost model for inertial navigation systems
A/MEITZLER, T. D.; B/GENET, R. M. Aerospace Guidance and Metrology Center, Newark Air Force Station, Ohio.
ABS:The purpose of this report is to document a mathematical model that has been used to evaluate the potential life cycle costs of inertial navigation systems. The model has been previously published, however, because of sensitive data, it had a limited distribution. This report includes definitions of all input and output parameters, explanations of algorithms for the model, a sample run using fictitious data and a program listing which includes a sensitivity study. ABA:Author (GRA)
AD-785392 AGMC-74-014-2 74/06/13 75N11922

Cost analysis of avionics equipment, volume 1
A/DODSON, E. N.; B/KORNISH, S. F.; C/LIEBERMAN, R. R.; D/WALLER, W. E. General Research Corp., Santa Barbara, Calif. (Science and Technology Div.)
ABS:The report addresses the problem of predicting the development, production, and logistic support cost of avionics equipment well before a detailed description of its physical makeup is known. The approach was to derive parametric cost estimating relationships (CERs) for four types of avionics subsystems: fire control radars, inertial navigators, digital computers, and Doppler navigation radars. These CERs are based on technical design variables familiar to the exploratory or advanced development design engineer. The development CERs incorporate an explicit measure of the development program's state-of-the-art advance. The logistic support CERs are functions primarily of equipment first unit cost or cumulative average cost. ABA:Author (GRA)
AD-781132 CRC-CR-1-419-VOL-1 AFAL-TR-73-441-VOL-1 74/02/00 74N32449

SECTION 2

APPLICATIONS

Life cycle cost lessons learned from the standard electronic module radar program

A/CORK, T. R.; B/BLAZEK, R. H. B/(Battelle Columbus Laboratories, Columbus, Ohio) In: NAECON '77; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 17-19, 1977. (A78-15551 04-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1977, p. 29-35.

ABS:The Standard Electronic Module (SEM) program, as defined in MIL-HDBK-246, is an ongoing DoD standardization program. Its aim is to achieve multiple benefits through standardization of common electronic functions at the circuit board level. The goals, objectives, and procedures of the SEM program strive to make available discrete SEMs which will reduce the cost and expedite the design and production of military electronic systems. In addition, several logistics supportability characteristics of electronic systems are influenced by incorporation of SEM's into the design. This paper describes the application of the SEM design technology to a specific Air Force avionics function and the approach and results of a sponsored research project which evaluates the life cycle costs of that SEM application. ABA:(Author) 77/00/00 78A15556

MICRON life cycle cost prediction model

A/GIBSON, K. J. A/(Rockwell International Corp., Autonetics Group, Anaheim, Calif.) In: NAECON '76; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 18-20, 1976. (A77-37352 17-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1976, p. 674-631.

ABS:MICRON is a strapdown inertial navigator which uses the microelectrostatically supported gyro. The MICRON model is analytical, employing cost estimating algorithms based on average maintenance rates, repair times, test characteristics, etc. Spares requirements are calculated using a Poisson cost minimization routine. Some parametric relationships are provided for estimating data page counts and training requirements. ABA:B.J. 76/00/00 77A37438

The Electronically Agile Radar's 'balanced design', and its importance to life cycle cost

A/MUKAI, D. M.; B/ATKINSON, P. E. A/(USAF, Avionics Laboratory, Wright-Patterson AFB, Ohio); B/(Westinghouse Defense and Electronic Systems Center, Baltimore, Md.) In: NAECON '76; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 18-20, 1976. (A77-37352 17-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1976, p. 379-386.

ABS:The Electronically Agile Radar (EAR) is being designed to be compatable with the B-1, B-52 or FB-111 weapons systems. It was decided to use an EAR design philosophy which balanced overall requirements such as performance, reliability, maintainability, nuclear survivability/vulnerability, and cost in such a way as to minimize the overall EAR life cycle cost. The objective of this balanced design concept is the elimination of the tendency of one requirement to drive the radar design to an unacceptable cost. ABA:B.J. 76/00/00 77A37402

Cost-effectiveness of refrigerated air for avionics cooling on wide-body commercial aircraft

A/BORONOW, W. S. A/(Douglas Aircraft Co., Long Beach, Calif.) ASME, SAE, AIAA, ASMA, and AIChE, Intersociety Conference on Environmental Systems, San Francisco, Calif., July 21-24, 1975, ASME 10 p.

ABS:The costs associated with initial procurement, maintenance, and spares provisioning of avionics equipment for current commercial aircraft accentuates the need to keep the cost of ownership to a minimum. This paper discusses the tradeoffs involved in adding a refrigeration system for avionics cooling to improve avionics reliability. The results of an analysis are presented parametrically for a typical wide-bodied commercial aircraft. The circumstances under which refrigeration is cost-effective and the cost reduction achieved for various operational conditions are identified. ABA:(Author)
ASME PAPER 75-ENAS-9 75/07/00 75A40892

The F-4E digital scan converter - An example of reducing the life cycle cost of avionics through digital technology

A/JARVIS, R. J. A/(USAF, Avionics Laboratory, Wright-Patterson AFB, Ohio) In: NAECON '75; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, June 10-12, 1975. (A75-37623 18-01) New York, Institute of Electrical and Electronics Engineers, Inc., 1975, p. 451-456.

ABS:A digital scan converter (DSC) for the F-4E aircraft is described which provides a means of displaying radar information, attack symbology, and electrooptical sensor imagery, all on a common indicator. The discussion covers system description and principles of operation, two flight test results, and life cycle cost analysis for the reliability and maintainability of the DSC equipment. It is shown that DSC exhibits increased reliability, maintainability, and growth capability over the analog scan converter, while simultaneously providing equivalent operational performance. ABA:S.D. 75/00/00 75A37679

DLS - New generation landing aid

A/BOEHM, M.; B/PEUKER, G. B/(Standard Elektrik Lorenz AG, Stuttgart, West Germany) Electrical Communication, vol. 50, no. 1, 1975, p. 70-76.

ABS:A new landing system proposal designated DLS (DME-based landing system, DME equals distance measuring equipment) is discussed. The system measures azimuth and elevation from the incidence of the aircraft's air-to-ground interrogating signals and transmits this angle information back to the aircraft. Advantages of DLS are outlined; among them are a good performance/cost ratio and the need to make only small modifications on existing systems in order to be implemented. The system can be operated wholly on those terminal DME frequency channels that are already allocated for use with ILS. ABA:S.J.M.
75/00/00 75A31421

Avionics cost development for civil application of global positioning system

A/KOWALSKI, S. H. Arinc Research Corp., Annapolis, Md.

ABS:This study of costs for avionics for civil use of the Global Positioning System (GPS), performed for the FAA Office of Systems Engineering Management (OSEM), was based on a uniform approach to cost estimating with the assistance of a pricing model. The system evaluated is the military-developed Z set with appropriate packaging modifications to meet the requirements of air carrier avionics standards and the less stringent environmental and packaging requirements for general aviation. ABA:Author (GRA)

AD-A056936 REPT-1326-01-4-1771 78/07/00
79N10040

Fiber Optics Cost Analysis Program (FOCAP)

A/ZELON, C. C.; B/CASSIDY, J. E.; C/SHIPLEY, R. G. Rockwell International Corp., Los Angeles, Calif. (Aircraft Div.)

ABS:The significance of this research is that it establishes methods for comparing the life cycle cost of fiber optics and wire data transfer systems on large military aircraft, and uses those methods to perform cost analyses on the data transfer subsystems. Using the B-1 as an example, the applicability of fiber optics to the B-1 avionics/electrical systems was identified. Conceptual fiber optics data transfer systems were designed. The present wire and the conceptual fiber optics designs formed a basis for computerized life cycle cost comparisons. Sensitivity analyses and cost trade-offs were performed to determine cost drivers in the application of fiber optics. Results show significance cost benefits can be gained by the implementation of fiber optics in data transfer subsystems having data rates in excess of 2 to 3 megabits per second. ABA:GRA

AD-A049859 NA-77-729 AFAL-TR-77-190 77/09/00
78N21105

Standard electronic module radar life cycle cost study

:/CORK, T. R.; B/BLAZEK, R. H. Battelle Columbus Labs., Ohio.

ABS:The Standard Electronic Module Program (SEMP) has been employed as a standardized design technology and logistics support concept by the U.S. Navy since 1962. From its original usage in shipboard systems, development of the SEMP has expanded to other electronic missions and to other services. The U.S. Air Force Avionics Laboratory initiated in 1974 an effort to evaluate the use of SEMP technology in the Air Force's avionics scenario. Under AFAL funding, the Naval Avionics Facility - Indianapolis has designed and fabricated an airborne weather-beacon-navigation radar system. Officially identified as the AN/APS-129, this radar is designed to perform the same function as the APN-59/B radar in C130, C135, and C141 aircraft. The purpose of this report is to present the results of an independent research program conducted to explore the benefits of SEMP technology as it is represented in the prototype APS-129 system. For analysis purposes, benefits are quantified in the framework of a retrofit program to replace the APN-59/B. ABA:GRA

AD-A045474 AFAL-TR-77-25 77/07/00 78N13305

Implementation of area navigation in the national airspace system: An assessment of RNAV task force concepts and payoffs

A/CLARK, W. H.; B/BOLZ, E. H.; C/SOLOMON, H. L.; D/STEPHENSON, A. R. Systems Control, Inc., Palo Alto, Calif.

ABS:The cost, operational impact, and economic benefits which are expected to accrue to the ATC system and various users of the National Airspace System as a result of the implementation of the Area Navigation were assessed. Previous impact analyses are expanded to include the primary aspects of ATC system operation and to include a broad spectrum of user groups, route structures, and types of operation. System impact results are presented pertaining to slant range effects, VORTAC requirements, ATC automation, airspace capacity, route development, charting, flight inspection, VNAV, controller training, and controller productivity. User impact results are presented in terms of fuel and time increment benefits for several classes of users, comparing 2D RNAV to VOR in the high and low altitude structures, and comparing 2D, 3D and 4D TRNAV to VOR/radar vectors in the terminal area. Estimates are made of total annual savings due to RNAV, and an analysis of user equipment cost versus benefits is presented.

ABA:Author
AD-A039225 FAA-RD-76-196 76/12/00 77N27096

A comparison between the AN/ARN-84 (V) and the AN/ARN-118 (V) TACANS, based on the life cycle cost
A/CUNDARI, L. A. Naval Weapons Engineering Support Activity, Washington, D. C.
ABS:TACAN (Tactical Air Navigation) equipments are being procured for the Navy, Coast Guard, and Air Force. The life-cycle costs and performance characteristics of different models of these equipments vary greatly. The two equipments currently being procured are the AN/ARN-84(V), for the Navy and Coast Guard, and the AN/ARN-118(V) for the Air Force. This report is a cost analysis based on the life cycles of these two equipments. It provides data intended to aid NAVAIR and OPNAV in making future procurements cost effective and responsive to both peacetime and war time TACAN requirements. ABA:Author (GRA)
AD-A035066 NAVWESA-R-7604 76/11/00 77N25145

A-7 ALOFT life-cycle cost and measures of effectiveness models
A/GREENWELL, R. A. Naval Electronics Lab. Center, San Diego, Calif.
ABS:Economic analyses are being conducted to determine the measure of effectiveness of fiber-optic and coaxial-cable systems for combat aircraft. Participating are the Naval Electronics Laboratory Center, Naval Postgraduate School, and the McDonnell Aircraft Company. The naval activities have developed a Bottoms Up model and McDonnell Aircraft Company has developed a Top Down model. These two models will be utilized to compare and analyze the optimum system in terms of performance and cost.
ABA:Author (GRA)
AD-A026206 NELC-TR-1982 76/03/01 77N15031

The A-7 ALOFT cost model: A study of high technology cost estimating
A/JOHNSON, R. L.; B/KNOBLOCH, E. W. Naval Postgraduate School, Monterey, Calif.
ABS:This analytical study contains the development of an appropriate life cycle cost (LCC) model for the A-7 Airborne Light Optical Fiber Technology (ALOFT) system. The model was developed to support an A-7 ALOFT economic analysis which will compare the total systems costs and performance benefits of an A-7 fiber optic linked navigation and weapons delivery system to existing or proposed wire interconnect designs. Major features of this study include the development of: (1) a process to derive cost estimates of a high technological development in the early conceptual stage; (2) an appropriate LCC model for the A-7 ALOFT economic analysis; and (3) fiber optic costing methodology to support the LCC analysis. This analysis is a follow-on study to An Approach to the Estimation of Life Cycle Costs of a Fiber Optic Application in Military Aircraft AD-A019 379. ABA:GRA
AD-A021913 75/12/00 76N31081

Cost analysis of the airborne portion of discrete address beacon system intermittent positive control (DABS/IPC) concept
A/KOWALSKI, S.; B/HASPERT, J. K.; C/WITT, J. Arinc Research Corp., Annapolis, Md.
ABS:The results of the cost and reliability evaluations developed for discrete and LSI versions of the airborne portion of the DABS/IPC concept were presented. To provide a basis for assessing the economic impact of DABS on the various aviation communities, separate cost evaluations have been developed for general aviation, commercial aviation, and the military. The expected cost of ownership to the individual aircraft owner was presented as well as the cumulative life-cycle cost to the user communities, based on the developed data. ABA:Author
AD-A023538/2 FAA-EM-76-2 75/12/00 76N26179

An approach to the estimation of life cycle costs of a fiber-optic application in military aircraft
A/MCGRATH, J. M.; B/MICHNA, K. R. Naval Postgraduate School, Monterey, Calif.
ABS:As significant technological advances in fiber optics and optical data transmission methods are being made, it is necessary to develop appropriate methods for estimating life cycle costs for alternative coaxial/twisted pair wire and optical fiber avionics. Measures of effectiveness are suggested for each alternative system. An approach, which structures the technological and demand uncertainties of fiber optics, is developed through scenarios as a means of relating cost and effectiveness. It is suggested that Delphi and experience curve techniques be used in conjunction with ordered scenarios as a technological forecasting technique for estimation of life cycle costs of fiber optics. In addition, a review of the historical and technological background of fiber optics and their application to the Naval Electronics Laboratory Center (NELC) A-7 Airborne Light Optical Fiber Technology (ALOFT) Program is included. ABA:GRA
AD-A019379 75/09/00 76N25017

Digital avionics information system preliminary life-cycle-cost analysis

A/PRUITT, G. K.; B/DIETERLY, D. L. Arinc Research Corp., Annapolis, Md.

ABS:A mathematical model was developed and exercised to evaluate the life-cycle costs of avionics developed according to the Digital Avionics Information System (DAIS) approach. The objective was to provide an initial estimate, based on available data, of the costs and cost savings associated with the DAIS concept. A comparative analysis was performed to estimate the relative costs of the avionics of four different aircraft types for both conventional and DAIS configurations. The results of this analysis were intended only to provide a perspective of the relative costs of DAIS and conventional avionics systems; they do not necessarily represent the true costs that may be encountered in an operational environment. The depth and accuracy of the estimates made in this report are necessarily restricted by the available data and the limited scope of the study. The DAIS costs are preliminary estimates or projections supplied by the DAIS Program Office at the Air Force Avionics Laboratory (AFAL). The data for the conventional avionics were extracted from many sources, including the Increase Reliability of Operational System (IROS) data system. Therefore, interpretation of the analyses contained in this report should be restricted to an assessment of the relative cost of the avionics integration approaches that have been addressed. ABA:GRA

AD-A017166 AFHRL-TR-75-34 75/09/00 76N21199

A-7 ALOFT economic analysis development concept

A/ELLIS, J. R.; B/GREENWELL, R. A. Naval Electronics Lab. Center, San Diego, Calif.

ABS:The economic analysis plan will establish the costs and benefits of applying future fiber optic technology to avionic cabling. Component descriptions, interface requirements, and the signal list for the A-7 (ALOFT) system are included to provide the necessary background to perform the economic analysis. ABA:Author (GRA)

AD-A013221 NELC/TD-435 75/07/07 76N13973

Implications of equipping a DC-8-61 fleet with RNAV/two-segment approach avionics

A/ANDERSON, E. B. United Air Lines, Inc., Denver, Colo.

ABS:Due to the costs of implementing two-segment approaches with special purpose computers, and the fact that such systems rely on special ground equipment not generally in use today, it is useful to consider the possibility of adding a two-segment approach capability to area navigation (RNAV) systems. The addition of the capability to provide two-segment approach navigation in an RNAV system which already interfaces with the standard instrument landing system is estimated to cost $1430 per aircraft. This includes the cost to add an approach progress display, to make necessary modifications to RNAV software, and to develop special approach plates.

ABA:Author

NASA-CR-137680 75/02/00 75N23544

SECTION 3

LIFE-CYCLE COSTS - GENERAL

Motivating contractors to improve avionics reliability and life cycle cost
A/LOVELACE, M. B. A/(USAF, Air University, Maxwell AFB, Ala.) In: NAECON '78; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 16-18, 1978, Volume 3. (A78-49851 22-04) New York, Institute of Electrical and Electronics Engineers, Inc., 1978, p. 1239-1245.
ABS:A majority of decisions impacting avionics life cycle costs are made by planners and managers in the strategy formulation period early in each program. These planners must be informed of the effects their decisions have on competition and contractor motivation to improve avionics reliability and life cycle costs. This paper surveys avionics studies and reports for Government and industry suggestions for improving contractor motivation. This review provides program managers and planners at all levels an appreciation for various suggested strategies and viewpoints. It provides an historical perspective which should result in better understanding during future avionics programs. ABA:(Author) 78/00/00 78A49993

FFF - Is it the key to the future in INS /Avionics reliability and life cycle cost/
A/SILVA, R. M.; B/ORAZIO, F. D., JR. B/(Vec-Tor, Inc., Dayton, Ohio) In: NAECON '77; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 17-19, 1977. (A78-15551 04-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1977, p. 1290-1298.
ABS:The paper examines the impact of the standard FFF (Form, Fit and Function) inertial navigation system specification on AFLC avionics reliability and life cycle costs. It is found that the FFF inertial navigation system becomes irrelevant and that the Single Agency becomes the perfect medium for the Air Force to concentrate an effort on upgrading system production processing. ABA:B.J. 77/00/00 78A15713

Environmental tests and logistics support costs
A/HERMES, P. H. A/(USAF, Aeronautical Systems Div., Wright-Patterson AFB, Ohio) In: NAECON '77; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 17-19, 1977. (A78-15551 04-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1977, p. 68-81.
ABS:The role of environmental tests in the acquisition process is reviewed. The purpose of, approaches to, and trends in environmental testing are given. The relationships between environmental and reliability tests are reviewed. The contributions to Logistics Support Costs (LSC) of avionic equipments are summarized which includes both the acquisition process, and the Operations and Support process. The impact of the various factorss contributing to avoidable LSC is reviewed with the conclusion that, because of the diversity of factors, significant LSC reductions can only be achieved by in-depth field investigations, using the combined resources of the acquisition, logistics, and operational organizations, to correct the LSC problem, and to feed back the lessons-learned to the appropriate organizations. ABA:(Author) 77/00/00 78A15560

Life cycle costing, a design tool - Nuances and caveats
A/LEONARD, K. C., JR.; B/WALLER, D. A. B/(Westinghouse Defense and Electronic Systems Center, Baltimore, Md.) In: NAECON '77; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 17-19, 1977. (A78-15551 04-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1977, p. 16-21.
ABS:This paper is primarily a collection of key life cycle cost analyses successfully performed on a variety of airborne avionic systems where the emphasis is on determining optimum design points rather than a sterile accounting of the potential acquisition and logistic support cost elements. Three key topics are addressed: analysis at the weapon system level, where availability is discussed as a function of projected usage level, reliability and logistics; subsystem analysis, where internal (to the subsystem) design tradeoffs involving parts quality, environmental constraints and partitioning are considered; and finally, a section highlighting constraints, potential inaccuracies, and pitfalls in the current LCC environment. Numerical examples are given in each area. ABA:(Author) 77/00/00 78A15554

A contractor's perception of design to life cycle cost
A/ADEL, R. E.; B/MERLINO, F. X. B/(Northrop Corp. Electronics Div., Palos Verdes Peninsula, Calif.) In: NAECON '77; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 17-19, 1977. (A78-15551 04-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1977, p. 12-15.
ABS:A review is presented of the design to life cycle cost (DTLCC) technique, using a typical inertial navigation system as an example. The detailed cost elements (standard values, government furnished data and contractor furnished data) that are used in the many DTLCC algorithms are analyzed. The analysis is conducted on the basis of a typical report matrix for unit production cost, expanded to include MTBF and MTTR values. ABA:B.J. 77/00/00

78A15553

Getting it right the first time

A/ALEXANDER, W. H. A/(Marconi-Elliott Avionic Systems, Ltd., Rochester, Kent, England) In: Symposium on Equipment and Systems Design for Minimum Cost of Ownership, London, England, March 16, 1976, Proceedings. (A77-22751 08-83) London, Royal Aeronautical Society, 1976, 11 p.: Discussion, p. D1-D7.

ABS:The paper is concerned with the problem of reducing the cost of ownership of avionic equipment by means of actions taken at the design stage. Cost of ownership is discussed in terms of procurement cost and cost of maintenance and support. Experience on reliability programs has revealed the need for a closed loop approach to reliability, the need for dedication for both customer and supplier to the reliability objectives, the need to quantify these objectives, the benefits of compulsion-inducement type contracts, and the importance of putting emphasis on the design phase. For most avionic systems there is a level of reliability which will give a minimum cost of ownership. Development of proper standards and a design review procedure are indispensable. ABA:S.D. 76/00/00 77A22757

Avionics proliferation - A life cycle cost perspective

A/GENET, R. M.; B/WEITZLER, T. D. A/(USAF, Plans and Analysis Directorate, Wright-Patterson AFB, Ohio); B/(USAF, Aerospace Guidance and Metrology Center, Newark Air Force Station, Ohio) Defense Management Journal, vol. 12, Jan. 1976, p. 60-64.

ABS:Avionics proliferation is referred to as the development, production, and fielding of a large number of different avionics systems performing the same basic function. Proliferation can therefore result in greater expenditures in research, development, production, and logistic support. A detailed computerized accounting-type life cycle cost (LCC) model is developed to obtain the cost estimates for three options of inertial navigational system: use of an existing inertial navigational system already in the inventory, use of an already developed off-the-shelf system not in the inventory, and development of a new system. The model data are discussed along with performance versus LCC. It is shown that by applying LCC analysis across multiple system applications, an avionics policy might be derived that precludes unnecessary proliferation without excluding the introduction of new systems which represent true advances in such areas as production cost and reliability over existing systems in the inventory. ABA:S.D. 76/01/00 76A18073

On setting avionic subsystem unit production cost goals

A/WEIMER, D. C. Institute for Defense Analyses, Arlington, Va. (Cost Analysis Group.)

ABS:Major avionics subsystems for candidate aircraft developed under the Design-to-Cost (DTC) acquisition concept were analyzed to gain additional insight into the critical production cost goal-setting process. The candidate aircraft sample consisted of the Air Force F-16 and A-10, the Navy F-18 and the Army Advanced Attack Helicopter. A total of 23 avionics subsystems assigned to the candidate aircraft were investigated. It was found that only six of the 23 subsystems met Department of Defense criteria for authentic DTC programs. The other subsystems were developed and acquired by airframe prime contractors on a competitive fixed-price basis with priced options for production. In these programs, competitive pricing replaced DTC goal-setting. Based upon limited research findings, it was concluded that subcontractor goal-setting was usually masked by competitive pricing practices: the resulting development programs did not have the schedule, cost, and design tradeoff flexibility to properly pursue the cost goal. It also was concluded that the goal establishment process, as observed for those 6 subsystems examined, was effective and did include appropriate important criteria for goal selection. ABA:GRA

AD-A051337 AD-E500020 IDA/HQ-77-19573 P-1280 77/10/00 78N24133

Avionics maintenance study

A/OWENS, P. R.; B/STJOHN, M. R.; C/LAMB, F. D. Air Force Avionics Lab., Wright-Patterson AFB, Ohio.

ABS:Avionics maintenance has become a major contributor to the life cycle cost of weapons systems and this study was undertaken to gain insight into factors contributing to the cost of avionics maintenance. To become familiar with the procedures employed and operating conditions encountered in the operational Air Force, a team from the Air Force Avionics Laboratory visited several avionics maintenance squadrons, along with depot organizations at Air Logistics Centers. Through interviews with both supervisors and maintenance technicians at these organizations, a familiarization with the working level procedures was acquired. Similarities and differences in procedures, personnel, test equipment, complaints, and equipment supported at installations under different major commands were noted. A wide range of avionics from old, tube type equipment through the latest solid-state equipment just being introduced into the inventory was considered in the selection of organizations to be visited. Difficulties in obtaining replacement parts and dissatisfaction with test equipment were found to be the problems most often voiced by maintenance personnel. To persons from a laboratory environment, the age of some

equipment still in use was shocking and the necessity for designing avionics to provide reliable service for 15 to 20 years was strongly realized. The need for early consideration of ATE requirements to insure rapid, cost-effective fault isolation in new avionics design is emphasized as one conclusion to the study. ABA:Author (GRA)

AD-A042568 AFAL-TR-77-90 77/06/00 78N10003

Avionic reliability and life-cycle-cost partnership

A/HARDY, C. A. General Dynamics/Fort Worth, Tex. (Research and Engineering Dept.) In AGARD Avionics Design for Reliability 14 p (SEE N76-24602 15-38)

ABS:The interface between the reliability and life-cycle cost of avionics weapon systems was discussed. The following areas were treated: (1) definition of life-cycle cost, (2) rationale for promoting the life-cycle cost concept, (3) analysis techniques used to evaluate the life-cycle cost, (4) the life-cycle-cost/design to cost requirements that are contained in present contracts, and (5) the interface between reliability and life-cycle cost during proposal, definition, and production phases. ABA:Author 76/03/00 76N24611

Avionics proliferation, a life cycle cost perspective

A/GENET, R. M.; B/WEITZLER, T. D. Aerospace Guidance and Metrology Center, Newark Air Force Station, Ohio.

ABS:The paper discusses proliferation and when it can occur. It specifically looks at the economic question of when can it be cost effective to use an existing military inertial navigation system for new aircraft rather than developing and using a new system. The discussion is from a life cycle cost viewpoint with particular attention to the 'start-up' costs. Attached with the paper is a complete reproduction of the input data and computer results used. ABA:GRA

AD-A016478 AGMC-75-002 75/07/30 76N21025

SECTION 4

RELIABILITY IMPROVEMENT METHODOLOGY

Cost-effective built-in test for advanced aircraft electrical systems

A/PERKINS, J. R.; B/JONES, J. L. B/(Vought Corp., Dallas, Tex.) (American Institute of Aeronautics and Astronautics, Aircraft Systems and Technology Meeting, Dallas, Tex., Sept. 27-29, 1976.) Journal of Aircraft, vol. 14, Dec. 1977, p. 1221-1225.

ABS:This paper presents a method for utilizing the data handling portion of the Advanced Aircraft Electrical System (AAES) to provide a cost-effective built-in test capability to isolate faults to the line replaceable unit (LRU). The evolved techniques provide a means for determining the health of each of the 2048 input and 2048 output controls (signal transducers and power switches) that are multiplexed by the system. The system also automatically tests the integrity of all the aircraft electrical distribution system signal and power wire, terminations, and connector pins. Four techniques to automatically test the data handling and multiplex circuits are also discussed. The built-in test (BIT) system as defined is efficient, small in size and weight, fully automatic, and cost-effective because most of the data and test circuits are time-shared to accommodate BIT data. The BIT data can be used inflight in power management equation solutions to permit programming of redundancy and safety interlocks. Two maintenance displays are discussed: a maintenance panel and an onboard strip printer. The BIT system is compatible with an air-to-ground data link of maintenance data. Also discussed are techniques for manufacturing and field checkouts of the system and wiring during manufacture and after field modifications. ABA:(Author)

AIAA PAPER 76-945 77/12/00 78A16183

Life cycle testing for avionics development

A/HANCOCK, R. N. A/(Vought Corp., Dallas, Tex.) In: NAECON '77: Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 17-19, 1977. (A78-15551 04-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1977, p. 46-53.

ABS:The paper reviews recent DOD avionics reliability improvement activities in developing the roles of laboratory and flight testing, with emphasis on the importance of the integrated test plan and involvement of all affected engineering disciplines. The status of DOD test standards revisions is discussed and a general assessment is made of the effect of these revisions on test procedures, facilities and costs. It is found necessary to use various degrees of life cycle event and environmental simulation when testing at the various systems levels from piece parts to total system. ABA:B.J.

77/00/00 78A15557

Avionics design for testability

A/COLEBANK, J. M. A/(Lockheed-California Co., Burbank, Calif.) In: NAECON '76; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 18-20, 1976. (A77-37352 17-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1976, p. 223-232.

ABS:The good and bad aspects of the testability of the avionics of the S-3A aircraft are reviewed. Attention is given to modularization, vast compatibility, built-in test features, design for throwaway, test points and ambiguity, configuration control, testability in future avionics, depth of test and diagnosis, and automatic test equipment characteristics. ABA:B.J. 76/00/00 77A37382

SEM - Building block for optimized avionics cost

A/STALEY, W. W. A/(Westinghouse Defense and Electronic Systems Center, Baltimore, Md.) In: NAECON '76; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 18-20, 1976. (A77-37352 17-33) New York, Institute of Electrical and Electronics Engineers, Inc., 1976, p. 51-57.

ABS:The objectives of the program to develop a Standard Electronic Module (SEM) for avionics are to reduce acquisition and maintenance costs and to improve reliability and availability of replacement parts. Attention is given to whether standardization is practical in avionics applications and what should the standardization be. It is concluded that there are no technical obstacles for a succesful SEM once proper incentives are provided. ABA:B.J. 76/00/00 77A37359

Avionics reliability. II

A/SWETT, B. H. A/(USAF, Analysis Div., Andrews AFB, Washington, D.C.) Journal of Environmental Sciences, vol. 18, Nov.-Dec. 1975, p. 20, 33-36.

ABS:Ways to test avionics performance and reliability under conditions of combined stress testing are discussed. Stress levels are proposed for various reliability-test situations, including thermal cycling, random vibrations, input voltage, humidity, acoustical stress, and altitude cycling. The necessity of using realistic test conditions to reduce total test time and costs is emphasized. ABA:F.G.M. 75/12/00 76A15446

Symposium on Designing from the Inside Out, London, England, February 6, 1975, Proceedings Symposium sponsored by the Royal Aeronautical Society. London, Royal Aeronautical Society, 1975. 106 p

ABS:Papers are presented dealing with design concepts for future aircraft systems in which emphasis will be on

human factors in order to improve cost effectiveness, safety, and comfort. Some of the topics covered include future flight deck design, data management within avionic systems, and improvements on freight and cargo areas. Individual items are announced in this issue. ABA:P.T.H. 75/00/00 76A15408

Design considerations for the minimum cost of ownership of avionics

A/CLEWS, D. A/(Marconi-Elliott Avionic Systems, Ltd., Rochester, England) In: Symposium on the Changing Balance of Design Requirements and How Designers are Reacting to It, London, England, February 26, 1975, Proceedings. (A76-15401 04-01) London, Royal Aeronautical Society, 1975. 13 p.

ABS:The growth of avionics is reviewed and advances in avionics technology are examined from the viewpoint of commercial effectiveness. The impact of Built In Test Equipment (BITE) is evaluated, and the problem of increasing unit complexity for the sake of BITE alone is considered. Increases of unit complexity greater than 10 to 15% are unlikely to be acceptable either on the grounds of cost or degradation in reliability. Improvements in the costs versus confidence level trade-off can be achieved by central organization of distributed BITE, but an economic limit is soon reached in analog systems. In digital systems, the success of BITE has been much more dramatic, where for very small hardware penalties, confidence levels of 90% are possible, but at the expense of software complexity. ABA:P.T.H. 75/00/00 76A15404

Design and development for maximum reliability and minimum maintenance costs

A/GRIGG, R. E. A/(Hawker Siddeley Aviation, Ltd., Hatfield, Herts., England) In: Symposium on the Changing Balance of Design Requirements and How Designers are Reacting to It, London, England, February 26, 1975, Proceedings. (A76-15401 04-01) London, Royal Aeronautical Society, 1975. 20 p.

ABS:The paper examines some design aspects which must be considered when the design criteria are maximum reliability and minimum maintenance costs for modern subsonic transport aircraft. Structure design and development to improve reliability and reduce costs and weight should progress parallel with requirements to improve safety levels and structural endurance. Main lines to follow would be to simplify load paths to avoid diffusion problems which are difficult to analyze, minimize the number of stress concentration areas by reducing cutouts and joints, and working to generally lower allowable stress levels. The design aim as far as system design is concerned is to enable the aircraft to complete its scheduled flight after a single failure has occurred without requiring any immediate crew action. New technology should only be used where a significant improvement is forseen that will bring real benefits, not problems. Later types of fire detection systems, such as pneumatic loops, would be more reliable and less costly than the double electronic redundant system and would have delay rates at least as good. Continuous monitor built-in test equipment has the advantage that faults are detected and displayed under actual operating conditions. ABA:P.T.H. 75/00/00 76A15402

Digital control and processing in airborne radar

A/CASE, W. N.; B/CROMER, O. M.; C/FRITSCH, R. J. C/(Westinghouse Electric Corp., Baltimore, Md.) American Institute of Aeronautics and Astronautics, Digital Avionics System Conference, Boston, Mass., Apr. 2-4, 1975, 9 p.

ABS:In recent years, the trend in airborne radar requirements has been from 'maximum performance' systems to 'balanced', 'designed-to-cost', 'cost effective' systems. The greater emphasis placed on reliability, maintainability, life-cycle cost and mode flexibility for both air-to-air and air-to-ground performance is causing a drastic change in the architecture of modern radar systems. Digital technology is playing a major role in meeting these new requirements. This paper shows, by example, where digital technology is providing decision-making, control computations, data processing, self-test and interface functions and what benefits are realized in terms of system requirements. Typical tradeoffs are considered; the growth of digital technology is illustrated and future applications are discussed. ABA:(Author)

AIAA PAPER 75-606 75/04/00 75A26746

Aircraft avionics environmental control analysis procedures for optimized life cycle cost

A/PLIZAK, B. T.; B/CAMPBELL, S. A.; C/TAYLOR, K. J. A/(U.S. Naval Material Command, Naval Air Development Center, Warminster, Pa.); C/(General Dynamics Corp., Convair Aerospace Div., San Diego, Calif.) In: National Conference on Environmental Effects on Aircraft and Propulsion Systems, 11th, Trenton, N.J., May 21-23, 1974, Proceedings. (A74-39733 20-28) Trenton, N.J., U.S. Naval Air Propulsion Test Center, 1974. 18 p. Navy-supported research.

ABS:The cost analysis procedures considered are concerned with the life cycle cost advantages of the various environmental control systems. These procedures can, therefore, be used to optimize the environmental control systems around life cycle cost. Examples of a use of the procedures for a fighter and an ASW aircraft are discussed. It is found that in both cases considerable cost savings can be realized by utilizing constant temperature

avionics. ABA:G.R. 74/00/00 74A39741

Improving Mean-Time-Between-Maintenance-Actions - A recommended system approach
A/PERDZOCK, R. C. A/(USAF, Wright-Patterson AFB, Ohio) In: NAECON '74; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 13-15, 1974. (A74-38517 19-09) New York, Institute of Electrical and Electronics Engineers, Inc., 1974, p. 325-331.
ABS:A wide discrepancy continues to exist between Mean-Time-Between-Failure (MTBF) for pieces of avionic equipment as determined from qualification tests and the Mean-Time-Between-Maintenance-Action (MTBMA) attained in operation. The present work discusses some of the probable causes for this discrepancy. Available data indicate that major strides can be made by improving Built-In-Test (BIT) and Aerospace Ground Equipment (AGE) design to assure that malfunctions are correctly diagnosed. It is urged that reliability testing and test of BIT and AGE capability be initiated as early in the design phase as possible. These tests should be carried out in stepwise fashion to allow a test-fix test concept against increasingly difficult test requirements. ABA:P.T.H. 74/00/00 74A38555

Reduction of environmental testing and analysis costs through simulation
A/HALEY, J. C.; B/NOWER, R. D. B/(USAF, Avionics Laboratory, Wright-Patterson AFB, Ohio) In: Cost effectiveness in the environmental sciences; Proceedings of the Twentieth Annual Meeting, Washington, D.C., April 28-May 1, 1974. (A74-36001 17-11) Mount Prospect, Ill. Institute of Environmental Sciences, 1974, p. 393-396.
ABS:Discussion of the use of dynamic analysis techniques for reducing costs of designing, developing, testing, and acquiring new and better reconnaissance systems. It is shown how significant cost savings can be realized when simulation and environmental testing techniques are employed at critical times during the research and development phases. ABA:M.V.E. 74/00/00 74A36037

Reliability as a capital investment
A/COPPOLA, A. A/(USAF, Rome Air Development Center, Griffiss AFB, N.Y.) In: Annual Reliability and Maintainability Symposium, Los Angeles, Calif., January 29-31, 1974, Proceedings. (A74-20926 08-19) New York, Institute of Electrical and Electronics Engineers, Inc., 1974, p. 349-357.
ABS:Using standard economic analysis procedures, a model was derived for computing the return in reduced maintenance costs of a system procured with a complete reliability program as compared to a system procured without reliability activity. Another model was formulated to compute the cost of a complete reliability program. Standard budgeting procedures were employed, including consideration of labor overhead, general and administrative overhead, and profit factors. The results indicated that reliability can be an attractive capital investment when acquisition costs are weighed against maintenance savings. ABA:(Author) 74/00/00 74A20965

avionics. ABA:G.R. 74/00/00 74A39741

Improving Mean-Time-Between-Maintenance-Actions - A recommended system approach
A/PERDZOCK, R. C. A/(USAF, Wright-Patterson AFB, Ohio) In: NAECON '74; Proceedings of the National Aerospace and Electronics Conference, Dayton, Ohio, May 13-15, 1974. (A74-38517 19-09) New York, Institute of Electrical and Electronics Engineers, Inc., 1974, p. 325-331.
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A/HALEY, J. C.; B/MOWER, R. D. B/(USAF, Avionics Laboratory, Wright-Patterson AFB, Ohio) In: Cost effectiveness in the environmental sciences; Proceedings of the Twentieth Annual Meeting, Washington, D.C., April 28-May 1, 1974. (A74-36001 17-11) Mount Prospect, Ill. Institute of Environmental Sciences, 1974, p. 393-396.
ABS:Discussion of the use of dynamic analysis techniques for reducing costs of designing, developing, testing, and acquiring new and better reconnaissance systems. It is shown how significant cost savings can be realized when simulation and environmental testing techniques are employed at critical times during the research and development phases. ABA:M.V.E. 74/00/00 74A36037

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A/COPPOLA, A. A/(USAF, Rome Air Development Center, Griffiss AFB, N.Y.) In: Annual Reliability and Maintainability Symposium, Los Angeles, Calif., January 29-31, 1974, Proceedings. (A74-20926 08-19) New York, Institute of Electrical and Electronics Engineers, Inc., 1974, p. 349-357.
ABS:Using standard economic analysis procedures, a model was derived for computing the return in reduced maintenance costs of a system procured with a complete reliability program as compared to a system procured without reliability activity. Another model was formulated to compute the cost of a complete reliability program. Standard budgeting procedures were employed, including consideration of labor overhead, general and administrative overhead, and profit factors. The results indicated that reliability can be an attractive capital investment when acquisition costs are weighed against maintenance savings. ABA:(Author) 74/00/00 74A20965

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14. Abstract

This Lecture Series No.100 on the subject of Methodology for Control of Life Cycle Costs for Avionics Systems is sponsored by the Avionics Panel of AGARD and implemented by the Consultant and Exchange Programme.

The continually increasing costs of avionics systems during acquisition and their lifetime operation is a matter of grave concern to the NATO family of nations. The NATO Governments need greater visibility and control over the life cycle costs of any weapon or avionic system.

Fortunately there have been formulated disciplined methods of providing such visibility and control over life cycle costs; that is over the development acquisition, training, operating and support and finally disposal costs.

It is proposed that the Avionics Panel sponsor a Lecture Series which presents the basic principles of Avionics Systems Cost Analysis in a rapidly changing technology environment and gives proven methods of achieving significant costs savings.

The Lecture Series will cover the following subjects: life cycle costing, design to cost, technology environment, costing of software, modeling and applications.

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